Iraq's calutrons

Electromagnetic isotope separation, beam technology, and nuclear weapon proliferation

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ISRI-95-03 — 19 October 1995

Abstract

The past and present status of high-current electromagnetic isotope separation (EMIS) technology for uranium and plutonium enrichment (i.e. calutrons) is reviewed in the five nuclear weapons states and in four critical states: Japan, India, Israel and Iraq.

The circumstances and significance of the 1979 discovery at CERN, the European center for nuclear research in Geneva, of Iraq's definite interest in calutron technology, is discussed in detail, together with the problem of publishing independent opinions on the nuclear proliferation implications of particle accelerator and fusion technologies.

The conclusion stresses the potential of "old" beam technologies such as calutrons, e.g., for the transformation of reactor-grade into weapons-grade plutonium, and of particle accelerators for the efficient production of plutonium or tritium. UN Security Council Resolutions 687 and 707, obliging Iraq to all proliferating nuclear activities, are shown to provide a legal precedent for the unambiguous definition of strictly peaceful nuclear activities. The "failure" of Western intelligence in detecting Iraq's gigantic calutron program is questioned, and the relation of this "failure" to the justification of past and possible future coercive counter-proliferation actions is investigated.

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Introduction

Shortly after the Gulf War, under the terms of UN Security Council resolution 687, several International Atomic Energy Agency (IAEA) teams inspected known or suspected nuclear sites in Iraq. Between June and September 1991, substantial enrichment activities were discovered, including two industrial-scale facilities using the electromagnetic isotope separation (EMIS) method, and a program to produce enriched uranium with ultracentrifuges. From that time on, the fact that Iraq did successfully put the EMIS method into practice, and the fact that Iraq had a complex, comprehensive nuclear weapons program, have been presented as big surprises and as major failures of Western intelligence. Why therefore, in the months before the Gulf War, did President Bush and his administration give such prominence to Iraq's nuclear bomb ambitions? "As I report to you, air attacks are under way against military targets in Iraq. We are determined to knock out Saddam Hussein's nuclear bomb potential," the President said, before ticking off other objectives of the assault, just two hours after U.S. warplanes began attacking Iraq on January 16, 1991.

There were many indications of Iraq's nuclear ambitions even before an Israeli air raid in 1981 destroyed the Iraqi Tammouz 1 (Osiraq) reactor just before its completion. For instance, the first author of this report (A. Gsponer) learned in 1979 that Iraq was already interested in the construction of an industrial-scale facility using the EMIS method [1]. This important discovery was one of the reasons why he decided to quit high energy physics and to start working full time on disarmament. With limited success, he tried to inform the arms-control/disarmament community of the military impact of particle accelerator technology, and in particular of their implications on both vertical and horizontal proliferation of nuclear weapons [1,2,3].

The purpose of this report is to review some of the historical and technical aspects of EMIS, to summarize what is publically known of Iraq's attempt to use this technology in its nuclear weapons program, and to draw the main disarmament conclusions.

In the first part, it will be seen that EMIS technology is an integral part of the nuclear programs of all nuclear weapons states (USA, Russia, England, France and China) and that it has been developed to various degrees in many countries including India, Israel and Japan.

In the second part, it will be seen that Iraq's EMIS design was not a simple copy of the rather crude one used by the USA during World War Two, but an improved design which incorporated many of the refinements made since 1945. In this part details of a biographical and historical nature will be given. For convenience, these will be referred to in the third person.

In the final part, it will be stressed that not only EMIS technology, but also a whole range of technologies, comprising old as well as new ones, are going to make nuclear proliferation an increasingly likely possibility. UN Security Council Resolution 687 and 707, which impose a comprehensive moratorium on Iraq in order to avoid the resumption of its nuclear program, and which recognize the proliferation potential of these technologies, are analysed in the perspective of their contribution to the unambiguous definition of strictly peaceful nuclear activities. Finally, the problem of the "failure" of intelligence to detect the massive Iraqi nuclear weapons program is addressed in the light of the discovery of Iraq's interest in calutrons as early as 1979.

The authors would like to thank Ms Heather Serdar, graduate student at The Graduate Institute of International Studies, University of Geneva, for sharing some of her documentation on the United Nations and Iraq with us. The authors thanks are also due to Ms Louise Dance for a considerable amount of work to ensure that the English language of the report became acceptable.

Chapter 1

Principle and state of the art in calutron technology

1.1 Enrichment technologies in perspective

There are two general methods for producing fissile materials for military or civilian purposes: breeding and enrichment. For a small or developing nation with limited military nuclear ambitions, in the absence of any technical or political obstacle, the cheapest and fastest option is breeding.

With breeding, a source of neutrons is used to convert a non-fissile material such as U-238 or Th-232 into fissile Pu-239 or U-233. The neutron source is generally a nuclear reactor or, possibly, a more complicated device such as a particle accelerator or (in the future) a fusion reactor [3].

In practice, a small fission reactor with a power of a few tens of MW(thermal) is sufficient to breed enough Pu-239 to make one atomic bomb per year. Such a reactor was built in Israel in 1960 and it is now widely accepted that it has been used to produce enough fissile material for several nuclear weapons. A reactor of similar size was used to produce the plutonium for the bomb India exploded in 1974. In 1981, concerned that Iraq could be developing nuclear weapons, an Israeli air raid destroyed the Iraqi 70 MW(th) Tammouz 1 (Osiraq) reactor.

In enrichment, the concentration of fissile U-235, which is only 0.72 per cent in natural uranium, is increased beyond the normal isotopic concentration. Weapons-grade uranium should be more than 80 per cent pure in U-235. A number of enrichment technologies are available; electromagnetic isotope separation (EMIS), gaseous diffusion, ultracentrifugation, laser isotope separation, plasma isotope

separation, etc. Of these technologies, gaseous diffusion is the most mature and the method on which the present industrial production is based. The physical principle of gaseous diffusion is such that plants using this method are necessarily very large and expensive. Since the existing diffusion plants are aging, two major alternatives for large scale commercial production (plasma and laser isotope separation) have been extensively studied. In the USA, it is the atomic vapor laser isotope separation (AVLIS) process that has been selected as the uranium enrichment method of the future [4]. And the plasma separation process (PSP) has been made available for other applications [5]. Both of these processes are technologically highly sophisticated and do not constitute a near term threat for nuclear proliferation in developing countries.

From the horizontal proliferation point of view, the ultracentrifuge method is now possibly the most attractive technique for building a relatively small enrichment plant — one which would turn out enough fissile uranium for one or two nuclear weapons a year. This method was used by South Africa and Pakistan to produce the fissile material for their nuclear weapons. Ultracentrifugation requires comparatively little energy and leads to small plants that can be easily concealed. Technologically however, ultracentrifugation is somewhat more sophisticated than electromagnetic enrichment, the technique which was historically the first to be used on an industrial scale and produced the uranium for the Hiroshima bomb.

Compared with the other enrichment methods, the main advantage of EMIS is that it uses only well known classical technologies (ion sources, vacuum, magnets, etc). Its main disadvantage is that it is not a continuous process. It involves a complicated and labour intensive series of physical and chemical tasks which pose considerable problems during plant operation. As shown by Iraq however, many of these problems can be alleviated by the use of microcomputer control systems.

1.2 Basic principle and main characteristics of EMIS

The electromagnetic isotope separation method is based on the principle that ions of the same energy, but of different masses, describe trajectories with different curvatures in a magnetic field.

At the heart of an EMIS system is an electromagnetic separator which comprises three main parts: a source in which the mixture of isotopes is ionized and the resulting ions merged into a beam which is accelerated to some energy; an analysing magnet providing the field in which the accelerated beam is separated

into as many beams as there are isotopes in the original mixture; and a receiver in which different pockets collect the ions from the separated ion beams. The source and the receiver are located in a vacuum tank situated between the pole faces of the electromagnet. Some residual gas is left in the vacuum tank in order to pinch and stabilize the ion beams. The associated chemical operations consist of preparing the feed-material (usually uranium tetrachloride), extracting the enriched material from the receivers (usually made of graphite) and cleaning the vacuum tank for recovering the material lost in the separator by scattering, sputtering and stray beams.

The most important parameters which characterize an electromagnetic separator are the ion *beam current* and the *mass separation power*. These two characteristics are antagonistic: a very high isotopic purity can only be achieved at the expense of a low current, which implies a low productivity. In practice, the dividing line between laboratory separators for high precision electromagnetic separation and industrial separators for high productivity is of the order of 1 mA (one milliampere). Here the term "calutron" refers to a production electromagnetic separator with a current of 1 mA or more.

In industrial scale separation, for various technical reasons, there is an upper limit of about 100 mA to the calutron beam current, which in the case of uranium, leads to a maximum enrichment of only 10 to 20%. There are two consequences. First, since the production of 50 kg of U-235 per year corresponds to a total beam current of over 100 A, there must be at least 1000 separators working in parallel to share the load. Second, in order to achieve a final enrichment of more than 90%, there must be a second enrichment stage which will require a somewhat smaller number (about 300) lower current but higher resolution separators. Hence, to produce enough U-235 for one atomic bomb a year a very large number of calutrons is required.

The most straight forward design of a calutron makes use of a uniform magnetic field, i.e. a field that is constant through space. In such a field the trajectory of an ion is a circle whose radius is a function of its mass. The basic arrangement consists of placing the source and the receiver in the field in such a way that after half a turn, both of the ion beams are caught by appropriately placed collector pockets (Fig.1a), one for U-238, another for U-235. This design, often referred to as the *180^{o} method*, was brought up from laboratory to industrial scale by E.O. Lawrence during World War Two [6] and now serves as a reference design for comparing other calutron designs.

The mass separation power is a function of two parameters: the *dispersion* and the *resolution*.

The dispersion is the spacing δ at the receiver between two beams of different masses. In the 180° method, the dispersion is given by the formula

$$\delta = R\frac{m}{M}$$

where M is the average beam mass and m the mass difference. Hence, in the separation of natural uranium (i.e. $M = 238$ and $m = 238 - 235 = 3$) with a calutron of mean beam radius $R = 100$ cm, the mass dispersion is of $100 \times 3/238 = 1.26$ cm.

The resolution ρ is given by the width of the beams at the receiver. This is a function of many parameters such as the width of the source, image aberrations (error in focusing), scattering on the residual gas, stability of the magnetic field, etc. For high intensity separators, the main contribution to the resolution is from the aberrations due to the angular spread of the initial ion beam. In particular, in the 180° method, if ions of the same mass leave the source at different angles, their trajectories do not meet at the same point on the receiver (Fig.1b). In the small angle approximation, the resolution is then

$$\rho = R\alpha^2$$

where α is half the opening angle of the initial beam.

For isotope separation to be possible, the width of the beams at the receiver must be smaller than their separation, i.e. $\rho < \delta$. Hence, from the above two expressions, it is seen that uranium isotope separation with the 180° method is only possible with beams of an initial divergence less than 6.4° (i.e. $\sqrt{3/238}$ radians), a rather small divergence for a high intensity beam.

To improve the resolution, and thus to enable separation of high intensity beams, various methods were studied during World War Two. The method finally used in Lawrence's calutrons was to make the magnetic field slightly non-uniform (by introducing specially shaped iron shims in between the pole faces of the magnet) in order to bring the beams to a better focus at the collectors [6]. After the War, in the period 1945-1955, many other methods were tested to improve the performance of electromagnetic isotope separation, a problem that is directly connected to the improvement of several closely related techniques such as mass spectroscopy and particle acceleration. In general, these methods tried to make use of non-uniform magnetic fields in order to improve the dispersion and/or the resolution, and thus to increase the separation power which may be characterized by the ratio δ/ρ .

An important example of an improved calutron design was invented in 1946 by the Swedish physicists Nils Svartholm and Kai Siegbahn [7] who were studying the general problem of momentum spectroscopy in a non-uniform field. They found that if the field decreases with radius going outward from the center of the orbits, there is focusing in the direction parallel with the magnetic field as well as normal to the field — the focusing is stigmatic. (If the field is uniform, there is focusing only in the radial direction.) In particular, in a magnet of rotational symmetry, if the field falls off in inverse proportion to the square root of the radius, maximum separation and focusing is obtained when the ion's trajectory through the field makes an angle of 255° between the source and the receiver. The Svartholm-Siegbahn method is therefore often called the *255° method*. In this method, the dispersion and resolution are given by

$$\delta = 2R\frac{m}{M}$$

and

$$\rho = \tfrac{4}{3}R\alpha^2$$

respectively. Thus, compared with the 180° method, while the dispersion is better by a factor of 2, the resolution is worse by a factor 4/3. The separation power is therefore only 1.5 times better. There is however, a further advantage in the Svartholm-Siegbahn method: because of the double-focusing effect of the non-uniform magnetic field, it is possible to use beams of higher intensity.

This discussion of aspects of the 255° method is typical of the kind of improvements possible over the standard 180° method: no break through is possible and only factor of two improvements are feasible. Nevertheless, by combining several such factors, substantial progress has been made since World War Two.

1.3 Sources of information on EMIS and calutrons

In comparison with other enrichment technologies, and more generally with the secrecy which surrounds the construction of nuclear weapons, essentially all the information concerning EMIS has been declassified since World War Two. In particular, the technical details of the American calutron program have been declassified in two steps. First, a series of fundamental research reports appeared in division I (Electromagnetic Separation Project) of the U.S. National Nuclear

Energy Series between 1949 and 1952. Second, a collection of specialized reports were declassified and started to appear towards the end of 1955 (Technical Information Service, Oak Ridge, Reports number TID-5210 to TID-5219). At the same time, many patents relating to the construction details of crucial calutron components were filed in the United States. This was the era of the optimistic "Atoms for Peace" program and it was believed that, apart from their scientific applications and potential to produce small amounts of separated isotopes for industrial and medical use, no country would ever turn to EMIS to produce the relatively large amounts of enriched material needed for atomic weapons.

The main practical reason for declassifying information on calutrons is that electromagnetic isotope separation involves no scientific or technological principle which could be effectively protected by a patent or kept secret. The principles of EMIS are common to several neighboring techniques which include mass spectroscopy, momentum spectrometry, electron microscopy and circular accelerator technology. EMIS is also a very important tool for fundamental research in nuclear physics (where it is essential for separating the various isotopes of a natural element in order to study their properties). All major components of an EMIS system (ion sources, magnets, vacuum system, high voltage power supplies etc) are widely used in all research laboratories which use low or high energy particle accelerators to study nuclear reactions or the interactions of elementary particles.

As a result, after the declassification of the information from the Manhattan project in the late 1940s and mid 1950s, most of the progress in EMIS technology is now reported in open scientific literature. Important sources of information are the proceedings of the twelve "EMIS conferences" which have taken place in Europe, the United States, Israel and Japan between 1955 and 1992. The proceedings of these "EMIS conferences" are generally published in the journal *Nuclear instruments and methods*, the editor of which is Kai Siegbahn, the co-inventor of the 255^{o} method.

Because of the intrinsic simplicity of EMIS technology, there has been no major break-through since the Manhatten project and those improvements made between 1945 and 1955. For this reason, most of the contributions at recent EMIS conferences are concerned with perfecting the many low-current separators used world-wide in fundamental or applied research. An increasing number of papers deal with the so-called *on-line* EMIS facilities, which are complex research instruments enabling the separation of very short-lived isotopes, and comparatively fewer papers with the standard *off-line* facilities. Exceptions to this are a few papers presented at the last two conferences. These gave information on several old Russian and Chinese high-current off-line EMIS facilities on which previously there was little information in open scientific literature.

1.4 EMIS in the United States

At the beginning of the Manhattan project, the method that would ultimately become practical for producing the fissile material for an atomic bomb was unknown. It was clear however, that any method that would process material in bulk would certainly be more efficient than any method, such as electromagnetic enrichment, that relies on passing small amounts of material through some kind of an analyser. For this reason, reactor production of plutonium, or gaseous diffusion of uranium, were expected to be the best methods. By mid-1942 no reactor worked and it was not clear whether an industrial scale gaseous diffusion plant would ever work. On November 5, 1942, General Groves decided that the design of the prototype electromagnetic separator, built by E.O. Lawrence at the University of California (hence the name "calutron"), would be frozen and that a plant called Y-12, with a capacity of about 100 grams per day would be created in Oak Ridge [8].

In Lawrence's original design, called "alpha", the evacuated tank containing the source and collector assembly was placed between the circular pole pieces of a large magnet originally intended for a cyclotron. This 184-inch magnet was completed in 1942 as a "mechanism of warfare", with an A-1-a priority for steel [8]. In Oak Ridge there were many calutrons to be put into operation. A simple rectangular dipole magnet was designed and the calutrons were assembled into ovals comprising 96 magnets alternating with 96 calutron tanks. This had the advantage of forming a closed magnetic loop and minimizing magnetic losses and steel consumption. In the end there were 9 such "racetracks", making 864 alpha calutrons in total.

In the alpha calutrons an attempt was made to get maximum possible output per separator, and one method of doing this was to use equipment of a fairly large size. The models adopted for production had a source-collector distance of 244 cm. The lateral width of the ion beam is limited by the dimension of the tank in the direction of the magnetic field, which was of the order of 3500 gauss. The tanks had an inside dimension of 61 cm and the lateral width of the ion beams was about 50 cm. The radial width of the beam varied from about 1 cm near the receiver and acceleration system to approximately 60 cm in the 90^{o} position [6].

The output of the alpha calutrons was enriched only to about 15%. To produce weapons-grade uranium, $8 \times 36 = 288$ improved calutrons were built to provide a second enrichment stage called "beta". The beta tank equipment, including sources and collectors, was made with linear dimensions just half the corresponding alpha dimensions. Beta calutrons worked with a lower current and emphasized recovery, not only of the further enriched output but also of the already enriched feed. Between January and June 1945, using feed from the alpha calutrons and the small

output of the gaseous diffusion plant, the Y-12 production was of 6 kg weapons-grade uranium per month [9, p.494]. Neglecting losses, such an output means that the average alpha and beta calutron currents were of the order of 150 and 20 mA, respectively.

By mid-1945, the gaseous diffusion process had demonstrated that there was a cheaper way of obtaining U-235 and soon after the cessation of hostilities, the electromagnetic plant was declared obsolete and the shutdown of the facilities was initiated. Only two of the nine buildings housing calutrons were retained intact — the pilot plant with two alpha and two beta separators and a production building containing 72 beta separators [10]. From that time on, these remaining calutrons were used for the production of enriched stable isotopes (embracing more then 250 different nuclidic species), and selected radioactive isotopes, for use in military, scientific, industrial and medical applications.

In order to increase the versatility of the Oak Ridge facility many improvements have been made over the years. In particular, to make it more suitable for multi-element enrichment, the original magnetic configuration (which linked the 72 beta calutrons into two sets of 36 separators in a common magnetic field) was modified. Installing 5 magnetic shunts resulted in the subdivision of the track into seven independent groups of calutrons. Moreover, six beta calutrons were modified into 255^{o} inhomogeneous magnetic-field separators to provide a factor of two enhancement in dispersion. In one calutron, the source and collector have been made external to the analysing magnet, providing a separation power roughly ten times that of the standard 180^{o} calutron, with a correspondingly lower ion throughput [11,12].

Apart from the large calutrons in Oak Ridge, many electromagnetic separators have been built in various universities and research laboratories. In 1981, Los Alamos National Laboratory and Lawrence Livermore National Laboratory decided to upgrade the quality of their isotope separation facilities to achieve better resolution and dispersion [13]. The project was named LLORIS, "Los Alamos, Livermore, Orsay Isotope Separator", the design was the result of a collaboration with the Laboratoire René Bernas of Orsay, France. A special feature of this 0.5 mA ion beam current separator is the use of a magnet with an adjustable quadrupole component. A total of three units have been constructed, two for Los Alamos and one for Livermore.

For future large scale enrichment requirements, the plasma separation process (PSP) is expected to provide the best option [12]. "In comparison with the calutron, the PSP has a lower enrichment factor and is capable of enriching only one isotope per pass. However, it is a very high throughput machine that could augment the present enrichment program by making available large quantities of material at

medium enrichments and by providing pre-enriched feed-material for the calutron" [11]. The main component of a PSP system is a large superconducting magnet [14].

1.5 EMIS in the Soviet Union

The first documented history of the Soviet atomic bomb has only recently been published [15]. The details of the enrichment program, and more particularly those concerning the diffusion and electromagnetic processes, are based on a document [16] by Igor Golovin, who worked closely with Igor Kurchatov in the 1950s and later wrote his biography.

Like the United States, the Soviet Union worked from the beginning on all possible enrichment methods. Work on electromagnetic enrichment started at the Kurchatov Institute of Atomic Energy in 1943 when the institute was founded [17], and was directed by L.A. Artsimovitch, I.N. Golovin and G.Ia. Shchepkin. Early in 1946, sites were selected for the gaseous diffusion plant, Sverdlovsk-44, central Urals, and the electromagnetic plant, Sverdlovsk-45, northern Urals. The first tests of the electromagnetic process were made in 1946 with the help of an electromagnet from Germany.

Things did not go smoothly for either the electromagnetic or the diffusion process. Artsimovich was unable to obtain ion sources with the required current. The problems with the diffusion process were even more severe. Construction of the production plant, which had a planned output of one kilogram U-235 per day, was completed in 1948. But, in 1949, the year of the first Soviet plutonium atomic bomb, the degree of uranium enrichment obtained was only 40 per cent. This 40 per cent enriched uranium was brought to Sverdlovsk-45, and after a month of round-the-clock work, Artsimovich and his group, using their experimental apparatus, managed to produce 400 grams of uranium enriched to 92-98 per cent [15, p. 191; 16, p. 20] (Neglecting losses and down-times, this corresponds to a total effective ion beam current of about 150 mA).

With the help of German scientists, the problems at the diffusion plant were solved at the end of 1950. At about the same time the priority for electromagnetic separation was reduced. It was decided not to build a large-scale electromagnetic plant, and the small plant at Sverdlovsk-45, which had already been completed, was no longer treated as a top-priority project.

As a reaction to Eisenhower’s "Atoms for Peace" proposal in 1953, a large amount of information was published on the Soviet achievement in the nuclear

domain. In particular, at the 1958 Atoms for Peace Conference in Geneva, a paper on electromagnetic isotope separation gave many details on more than a dozen large electromagnetic separators of various types, then operational in the Soviet Union [18]. Of special interest were the largest separators which had a two-story, four-tank design within a single 400 tons magnet. Such characteristics suggest that these calutrons were the prototypes for the Sverdlovsk-45 plant. Photographs of these calutrons can be seen in the paper [18, Fig.2] and in a booklet distributed at the 1958 Atoms for Peace exhibit [19, p.53].

In 1957, L.A. Artsimovitch and others published a particularly elegant example of a high-resolution calutron using the 255^{o} method [20]. (In fact, for some technical reasons, the focusing angle was 225^{o} instead of the optimum 255^{o} value.) This design used a magnetic field of rotational symmetry and provided excellent single-pass enrichment for heavy elements such as uranium or plutonium with ion beam currents of the order of 10-15 mA.

In 1969, an electromagnetic separator, S-2, especially designed for high efficiency separation of isotopes of the heavy radioactive elements which have a small relative mass difference, was built in Arzamas-16 [21], the Soviet equivalent of the Los Alamos laboratory. The magnet is C-shaped and the pole tips have a slope creating a field which decreases in inverse proportion to the radius of the beam trajectory. The ion source provides a beam of up to 10 mA. Although Arzamas-16 was originally a Soviet military laboratory, isotopically pure samples in the form of layers, targets, solutions or other forms may now be obtained elsewhere on a contractual basis [22].

The future of enrichment in the USSR was discussed by A. Tikhomirov at the EMIS-12 conference [17]. The centrifugal method, which was considerably developed in the USSR and led to a practical plant in 1959 at Sverdlovsk-44, was presented as a good option for the large scale enrichment of medium weight isotopes (such as germanium for semiconductor applications). However, the plasma separation process (which in contrast to the centrifugal one does not require volatile compounds) is seen as an important option for the future. In particular, it can be compared with the electromagnetic method in universality, and the centrifugal method for the productivity. A similar conclusion had earlier been reached by J.G. Tracy in an assessment of the future of enrichment from an American perspective [12].

1.6 EMIS in the United Kingdom

A comprehensive review of the state of the art in electromagnetic enrichment in the 1950s, giving details on the British and French early calutron efforts (as well as some details on similar efforts in other European countries, South Africa and Japan), was published in 1958 [23]. The British project was started in 1945 by some of the British scientists who had been working for the Manhattan project. They designed units similar to those they had been working on in the U.S.A. The first separator built at Harwell (south of Oxford), completed early in 1950, was a 24-inch beam-radius separator similar to the American beta calutron.

The main purpose of this large capacity 180^o machine was to produce material in sufficient quantity rather than to obtain very high enrichment. Due to the success of the Capenhurst diffusion plant, which came into operation between 1954 and 1957, there was no need to further develop the high production calutron technology. Both scientific and military applications however, demanded smaller quantities of highly enriched materials, for which a beam current of the order of 1 mA is sufficient.

A disadvantage of the 180^o type of machine is the restriction placed on the source and receiver design because of the cramped space and the magnetic fields in the region of these units. In order to obtain high enrichment factors, a solution is to consider a "sector machine" in which the source and collector are external to the magnet. This led to the construction in Harwell of HERMES, "Heavy Elements and Radioactive Material Electromagnetic Separator", in which the ion beam trajectory made a 90^o angle at a 48-inch radius in the magnetic field [23, p.150-165].

Typical applications of HERMES comprise the separation of plutonium isotopes [23, p.165]. At Oak Ridge, U.S.A., a beta calutron had been modified for the same purpose while a smaller version had been constructed for use as a second stage machine [23, p.165]. In the U.S.S.R., the 225^o machine of Artsimovich had been specially designed for the separation of radioactive heavy elements such as plutonium [20].

1.7 EMIS in France

In 1940, Alfred O. Nier at the University of Minnesota in collaboration with Booth, Dunning and Gross at Columbia University, were the first to use the electromagnetic method to separate the uranium isotopes in order to investigate

their fission properties [24]. René H. Bernas, who studied physics at the University of Minnestota and was to become the leader of electromagnetic separation in France, developed a high current version of the type of separators ordinarily used in Nier's laboratory [25]. In France in 1952, Bernas built a 60^o sector machine with an ion beam radius of 50 cm [23, p.82-95]. This separator was installed in a laboratory of the Commissariat à l'Energie Atomique (CEA), Saclay. In September 1955, out of 290 hours of collection time, 200 were dedicated to uranium with a production of 1.4 gram of U-235 [23, p.93], corresponding to an effective beam current of 0.1 mA. The success of the French machine was a positive factor in the British decision to build HERMES.

Contrary to the United States, England and the Soviet Union, there has been no attempt in France to pursue simultaneously the uranium and plutonium routes to atomic weapons. Indeed, in 1952, France chose plutonium as the priority for its own nuclear weapons program. Therefore, the construction of the first French uranium enrichment plant, using the gaseous diffusion process, started in 1960 only. The Pierrelatte enrichment plant became operational in 1964 and was completed in 1967. It is interesting that at about the same time some effort was made to build large size calutrons. In effect, a 255^o double focusing calutron operating with a maximum ion beam current of about 150 mA, was built in Saclay between 1962 and 1965 to produce isotopes in commercial quantities [26]. In the construction of this device, several field configurations were tested. Similarly to the Oak Ridge calutrons [8,10], this 24-inch separator was based on an ordinary rectangular magnet (which normally creates a uniform field). The required non-uniform field was obtained by introducing suitably shaped iron "shims" between the pole pieces [27]. While experiments with linear shims (corresponding to the 180^o method) enabled the use of ion beam currents with maximum intensities of the order of 100 mA, circular shims (corresponding to the 255^o method) enabled the use of currents of the order of 200 mA, clearly demonstrating the superiority of 255^o method. An important aspect of the publications describing this work is that they provide a good summary of the mid-sixties' state of the art in industrial-scale EMIS technology [26,27]. In particular, they show the usefulness of computer programs to study complicated non-uniform field systems and the simultaneous focusing of two separate ion beams.

In France, as in the other countries which have mastered the technique of gaseous diffusion, calutrons have not become a means for large scale production of enriched uranium. Over the years however, several large separators were built in order to suit various other needs. For example, at the "Laboratoire René Bernas", in Orsay, two separators, SIDONIE and PARIS, were built to prepare extremely enriched isotopes [28]. PARSIFAL, a separator providing safe handling of radioactive materials, was built at the military laboratory of Bruyère le Chatel

to separate specific isotopes from a strong radioactive background [29]. Typical applications are the purification of very small quantities of isotopes, with half-lives greater than 12 days, that are produced in special monitoring targets exposed to the neutron flux of a reactor or nuclear explosion. To increase the availability of PARSIFAL, a copy of the source block was built in 1990, so that secondary operations such as source-outgassing could be performed at the same time as actual separation using the other source [30].

Expertise gained by French scientists in the design and construction of high resolution electromagnetic separators led to a collaboration with the EMIS specialists at Los Alamos in an effort to upgrade the isotope separation facilities at the Los Alamos and Livermore nuclear weapons laboratories [13]. This is a typical example of the collaboration/competition relationship characterizing the arms race between France and the United States since the early 1980s, and even more so since the break up of the former Soviet Union. Where each state in relation to the other takes the place of the Soviet Union as the challenger in the development of the most sophisticated military technology.

In order to replace its aging gaseous diffusion facilities, France has perfected the AVLIS process (SILVA in French) and expects to build an industrial scale laser enrichment facility by 2010.

1.8 EMIS in China

Details on Chinese calutrons began to appear in open scientific literature in the proceedings of the EMIS-10 conference [31]. The main characteristics of the four calutrons built at the China Institute of Atomic Energy, Beijing, are given in these articles, and a summary of the elements processed from 1965 to 1986 was given at EMIS-11 conference [32].

A laboratory-scale 90^{o} separator (F-1) was installed in 1962. Since then two 180^{o} production separators (F-2 and F-3) have been installed in 1965 and 1968 respectively, and a 255^{o} double-focusing separator (F-4) was constructed in 1980. A comparison of the characteristics of F-2 and F-3 with those given in 1958 for the Soviet calutrons, show that they are in fact identical to the two large single-tank calutrons (with 220 and 280 tons of magnet weight) previously built in the USSR [18]. The summary of the elements processed shows that the first elements to be isotopically separated were lithium and uranium, clearly indicating that the applications were connected with the Chinese atomic weapons program. These separators are still in use. A computer-aided inspection system was developed as

a first step in designing a computer control system to improve the quality of the products and reduce operator supervision [33].

Since Soviet aid to China in the 1950s and 1960s included help in the construction of a gaseous diffusion plant, the Chinese calutrons have not played a direct role in the large-scale production of enriched uranium. Recently, the Chinese know-how in calutron technology has become an element of concern for the proliferation of nuclear weapons. Indeed, the agreement that China signed with Iran in 1990 includes the shipment of several million dollars worth of calutron equipment [34].

1.9 EMIS in India

A laboratory-scale 255° isotope separator, designed after the spectrometer originally built by Svartholm and Siegbahn [7], was completed in 1958 at the Saha Institute of Nuclear Physics, Calcutta [35]. The construction of this EMIS device took place at the time of the construction of the research reactor supplied by Canada. This reactor began operating in 1960 and was used to produce the plutonium for the 1974 Indian nuclear explosion.

This separator was modified in the mid-1980s in order to be used for off-line separation of short-lived isotopes produced using the variable-energy cyclotron of the Bhabha Atomic Research Center [36].

1.10 EMIS in Israel

Israeli activities in the domain of EMIS were described at the EMIS-8 conference of 1973 and further explained at the EMIS-9 conference which took place at Kiryat Anavim, Israel, May 10-13, 1976. The two basic instruments developed in Israel for this purpose, the SOLIS and MEIRA separators, are operating at the Soreq Nuclear Research Center.

The Soreq on-line isotope separator (SOLIS) is connected to a fission source placed at an external beam port of the Soreq Research Reactor. It is a research instrument dedicated to the study of short lived isotopes produced in the fission of U-235 [37].

The separator MEIRA is a high output electromagnetic isotope separator whose typical source oven charges are one hundred grams and beam currents are of the or-

der of 50 mA. "The aim of the MEIRA development was not to arrive at the highest quality mass analysis, but to invest the minimum development, in both equipment and modifications, in order to arrive reliably at the required analysis capability [38]". This capability is typically the production of high purity tellurium-124, as is required for the production of iodine-123 for radiopharmaceutical applications [39]. The first objective of MEIRA however, has been the "systematic experimental investigations (leading to) an understanding of the basic phenomena in the separation process [39]". The depth of this understanding can be measured by the fact that tellurium-124 at a purity in excess of 99% has been obtained in a single pass with MEIRA [39]. Following this success, an automatic system, allowing for unattended operation after the initial adjustment of the separation conditions, was developed [40]. The nuclear proliferation significance of the MEIRA separator is that it has the capability of efficient separation of plutonium isotopes, and shows that Israel has mastered the technological challenge of building high productivity calutrons for uranium enrichment or plutonium purification.

The key man behind the development of high current EMIS technology in Israel is I. Chavet who received his PhD in France while working on the Orsay separator built by R. Bernas [40]. The Orsay separator (i.e. a sector-type separator derived from the one Bernas built in Saclay in 1953) is the model on which MEIRA was built.

1.11 EMIS in Japan

Until the EMIS-11 conference in 1986, at which it was agreed that the following EMIS conference would be held in Japan, there was little information published on Japanese calutron activities in non-Japanese publications. The participation in EMIS conferences by Japanese scientists was minimal. At EMIS-11, as an introduction to a review paper on the on-line separator facilities in Japan, M. Fujioka presented a brief history of off-line isotope separators in Japan [41]. As early as 1941 an isotope separator was used for mass separation and identification of a radioactive isotope, sodium-24. This study was made as a test experiment for a larger research project concerning fission products. Construction of a larger isotope separator of 180^{o} deflection for such a purpose was started but interrupted due to World War Two. At that time there were five existing cyclotrons in Japan. They were seized by the Americans on November 20, 1945, and totally destroyed [42]. According to a leading Japanese physicist, a student during the War, Japan's atomic bomb effort focussed on enrichment. Two approaches were pursued, the electromagnetic separation of uranium-235 and separation by a thermal diffusion

process [43]. The thermal process was abandoned before the end of the war and, according to the Japanese physicist, "... if we spent 100 times more in research effort, we could have developed the bomb in one year".

The construction of off-line separators (mainly for stable isotopes) started again ten years after the War. Two small separators were built in 1955. Then followed the construction of four separators in succession. All four are of the Bernas or Saclay type, and were built in 1956, 1958, 1959 and 1961. The last separator, which is the only isotope separator constructed for off-line use that is still working today, has been used up to the present mainly for implantation experiments using stable as well as radioactive materials [41].

EMIS-12 was held at Sendai, Japan, 2-6 September 1991. Out of 149 registered attendees, 91 were from Japan and 58 were from elsewhere. There were several contributions regarding on-line separation and related technical problems, a subject on which Japanese scientists have developed considerable expertise [41]. There were also four contributions concerning off-line isotope separation dealing with ion cyclotron resonance and plasma separation processes [44]. These later contributions are an indication that, besides laser isotope separation, Japan might be interested in new enrichment technologies which have the capability of separating in industrial quantities, all kinds of isotopes, including uranium or plutonium. In effect, contrary to laser isotope separation, which may require different types of lasers for different isotopes, the plasma separation process is much more flexible because all parameters are continuously adjustable.

1.12 EMIS in other countries and at CERN

In the previous sections, EMIS activities have been reviewed in the five nuclear weapon states and India, Israel and Japan. Similar activities, at one level or another, for either scientific or industrial purposes, are under way in many industrialized countries, especially in Europe. Since the previous coverage includes most of the countries (except Germany) which have significant nuclear activities, they will not be reviewed in detail.

A special case has to be made for CERN, the European nuclear research center in Geneva, Switzerland. When CERN was created, in 1954, nuclear physicists and accelerator specialists from all over Europe came to Geneva and played an essential role in the highly successful development of the laboratory. These people were to become staff members as machine designers or researchers, or to become users of the CERN facilities while remaining attached to their home university. Let us just

mention two people with direct previous experience in off-line and on-line isotope separation. C.J. Zilverschoon, who's PhD thesis (University of Amsterdam, 1954) was on the construction of the "Amsterdam Separator", originally designed as a production machine and later used for more academic studies [23, p.119], was to join the CERN staff and become a leading accelerator scientist. And O. Kofoed-Hansen who, in 1950, with K.O. Nielsen, was to perform the first experiment to make use of the beams of short-lived radioactive nuclei produced by an on-line electromagnetic separator [45]. Kofoed-Hansen became a major advocate and user of the worlds largest on-line separator, the Isotope Separator On-Line (ISOLDE), built at CERN in 1967 [46].

While CERN's mission was clearly defined in 1952 as a laboratory for fundamental research in high energy nuclear physics, using the various large accelerators to be built in Geneva, it was also to become a centre of excellence in many specialized technologies with considerable industrial or military potential [47]. That this was clear from the beginning is indicated by the explicit mentioning of "isotope separation and beryllium engineering", as examples of specialized technologies in which CERN had to collaborate with external institutions [48]. As a result, in time, CERN became a world leading institution, not just in pure science, but also in many advanced technologies of importance to various nuclear activities including electromagnetic separation of isotopes, together with a tradition of openness and international collaboration which was to make it an ideal place to acquire detailed information on such technologies.

Chapter 2

Iraq's calutron program

2.1 Spring 1979 at CERN

In 1979 André Gsponer was at CERN working on an experiment, NA10, designed to measure, with good statistics and good mass resolution, the production of high-mass muon pairs by pions. The apparatus (Fig.2) consisted of a beam dump followed by a high-resolution spectrometer whose central piece was a large toroidal magnet (for a detailed description of the apparatus see reference [49]). In the experiment, Gsponer was responsible for the data acquisition system, while Klaus Freudenreich was the physicist in charge of the magnet. In Spring of 1979, Freudenreich informed Gsponer that he had recently been visited by an Iraqi engineer wanting to know everything about the magnet, including all sorts of construction details. As a justification for his interest, he claimed that he was motivated by the possibility of using such a magnet for storing electromagnetic energy. But, for such an application, a superconducting magnet would have been necessary, and the NA10 magnet was a conventional one. This contradiction prompted the discussion between Freudenreich and Gsponer.

While the NA10 magnet was non-superconducting, it was a very special one, and unique in the world at least because of its size. In particular, it had the property of maximizing the amount of magnetized air (through which high energy particles can pass with minimum disturbance), while minimizing the amount of steel. Since the magnet had an axial symmetry, its construction had required the resolution of a number of difficult engineering problems. It was well known to all physicists of the NA10 collaboration that Mario Morpurgo, the designer of the NA10 magnet and one of the world's greatest specialists of magnet technology, considered the NA10 magnet as one of his masterpieces.

Gsponer knew that during World War Two, in the Oak Ridge Y-12 plant, there were hundreds of calutrons working in parallel. Each of them consisted of an evacuated separation tank placed in a magnetic field. In Y-12, the magnets providing the field and the calutron tanks were assembled into ovals comprising 96 calutrons: this had the advantage of forming a closed magnetic loop and of minimizing magnetic losses and steel consumption. If this optimization process is pushed to its limit, the result is a configuration which looks like a cut through an orange, with one slice made out of steel, and the next one empty to contain a calutron tank. This is exactly what the NA10 magnet looked like (see lower part of Fig.2), with room for six calutron tanks and a clever design calculated to use as little steel as possible.

The conclusion was that the Iraqi engineer was most probably interested in a magnet for electromagnetic isotope separation. Due to the nature of the technical questions asked by the engineer, it was quite possible that Iraq, at the time, was already comparing the engineering problems of various options for the construction of an industrial scale EMIS plant. According to Freudenreich however, its seems that the Iraqi engineer did not get access to the engineering drawings, nor to the specific processes developed by CERN for the construction of the NA10 magnet.

2.2 Jafar Dhia Jafar and the origin of Iraq's calutron program

When the Iraqi engineer came to CERN to gather technical information on the NA10 magnet, he introduced himself to Freudenreich as having been sent by Jafar Dhia Jafar, an Iraqi physicist who had worked with Freudenreich at CERN in the 1970s. Jafar who was to become the head of Iraq's atomic bomb program, was trained as a high energy physicist at the University of Birmingham and at Imperial College, London. Between 1967 and 1976 he published 12 papers on various high energy physics experiments, first at the Birmingham synchrotron and later at CERN. The results of the experiment on which Jafar had worked with Freudenreich were published in 1975, at which time Jafar was back in Iraq and working at the Nuclear Research Institute, Baghdad [50]. (The connections between Jafar and Freudenreich, and later those between Freudenreich and Gsponer, are illustrated in Fig. 3, in which the front pages of references 49 and 50 are reproduced.)

The return of Jafar to Baghdad in 1975 coincided with the start of a government drive to recruit nuclear scientists [51]. By 1979, Jafar became Vice Chairman of the Iraq Atomic Energy Commission and was responsible for dealing with the

French on Osirak, the French nuclear reactor under construction in Iraq. On April 7, 1979, two days before a pair of reactor cores were to be shipped to Iraq, seven Israeli agents broke into a warehouse in the port of La Seyne-sur-Mer, near Toulon, and blew them up. On June 13, 1980, an Egyptian chemist hired by Iraq to work on spent fuel reprocessing was killed in Saclay were he had been sent for training. On August 7, 1980, the office of the Italian firm that supplied plutonium reprocessing technology to the Iraqis, was bombed. Finally, on June 7, 1981, Israeli aircrafts dropped several bombs on Osirak, scoring enough hits to permanently knock out the reactor.

The destruction of Osirak is certainly the first deliberate act of "counter-proliferation", and the event that must have given priority to uranium enrichment over plutonium production in Iraq's nuclear weapons program. The assertion put forward by most analysts, i.e. that Iraq's calutron effort started *after* the bombing of Osiraq, is not plausible. In common with all other nations with nuclear weapon ambitions, all possible options for either producing plutonium or enriching uranium must have been studied right from the beginning. As has already been stressed, the production of plutonium with a small reactor was certainly the easiest route. But, in the case of Iraq, the visit of an Iraqi engineer to CERN in 1979 indicates that a significant amount of theoretical work on calutrons had already taken place. Not only because the engineer was inquiring about the construction details of a large magnet, but also because a clear understanding of the special properties of this unique magnet was shown. In addition, the mere knowledge that such a magnet had been built at CERN, could only have been obtained after a thorough investigation of both calutron theory and the state of the art of magnet construction. In this context, the fact that Jafar personally knew the man in charge of the NA10 magnet, Freudenreich, appears as a pure coincidence, a favorable circumstance which he tried to exploit, and not as the starting point of some new investigation.

Of course, since nothing is known by us about the connections between Jafar and Iraq's secret nuclear weapons program while he was in Europe, it is not possible to know what role Jafar played in the early days of Iraq's nuclear program. In particular, we do not know if Jafar had anything to do with this program when, after graduation at Birmingham and before joining Imperial College, he spent some time in 1968-1969 at the Nuclear Research Center, Baghdad [52]. Later, when Jafar worked with Freudenreich at CERN, it was well known in the experimental team that Jafar had been an officer in the Iraqi army, and jokes were made because another member of the team was a reserve officer in the Israeli army. Nothing can be inferrerd by this, military service being an obligation in both countries. It is interesting however, to point out the irony of this collaboration. Neither do we have confirmation of the possibility that Jafar had a look at the British calutrons while working at Harwell, or at the near-by Rutherford Laboratory, as

it is suggested by Burrows and Windrem [51, p.36]. What is clear, is that when Jafar returned to Baghdad in 1975, because of his background as a high energy physicist, it must have been more natural for him to work on calutrons than on the other parts of the program. Later, after the bombing of Osirak, when enrichment became the preferred option, Jafar was in a leading position at the Iraq Atomic Energy Commission. It must not have been too difficult for him to push the calutron method: compared to the centrifuge technique it required much less foreign expertise and it was likely that he had a well studied design ready to be tested in a pilot plant.

In order to understand Iraq's calutron design, and to appreciate the significance of Jafar's interest in the NA10 magnet, it is important to examine first its potential as an analysing magnet for a calutron.

2.3 The NA10 magnet as a calutron magnet

In 1977, a group of Swiss Federal Institute of Technology physicists (including Freudenreich and Gsponer) proposed an experiment at CERN to study the inclusive production of massive muon pairs with intense pion beams. They suggested in their letter of intent [53] the use of an axially symmetric spectrometer consisting of four magnetized iron toroids, with various detectors placed in between. Once the experiment was accepted, it was found during the preparation stage, that a much better technique than magnetized iron could be used for the magnetic analysis. The idea came from Mario Morpurgo, one of the original builders of CERN, who came to Geneva after his studies in Rome and immediately applied his intelligence to the design and construction of conventional magnets [54].

Morpurgo's idea was to build a large scale version of the six gap "orange" spectrometer built in 1955 at Risø, Denmark, by O.B. Nielsen and O. Kofoed-Hansen [55]: while the Risø magnet had a 0.25 meter radius and a length of about 0.5 meter, the NA10 magnet was to have a 2 meter outer radius and a 4.8 meter over-all length. A section through the Ris¿ spectrometer can be seen in Fig.4 and a similar section through the NA10 magnet can be seen in Fig.2. For the experimenters, the advantage of this magnet over the use of magnetized iron is that the magnetic analysis could be done by measuring the deflection of particles travelling through air instead of steel, thus with a subtantially better resolution. And for Morpurgo, the construction of such a magnet was a challenge, a special design which implied the use of several unusual techniques.

Like the Risø magnet, the NA10 magnet has hexagonal symmetry [49]. An

essentially azimuthal field $B = B(r)$ is excited between six laminated, wedge-shaped, iron pole pieces, each subtending 18° in azimuth. The air-core part of the magnet, consisting of sectors between the iron wedges, thus subtends 70% of the azimuthal acceptance. Over almost the entire air-core volume, the field has a $1/r$ dependence with a high degree of precision. The $1/r$-dependence of the field is useful for the magnetic analysis of particles of both low or high energy. That such a field, instead of a uniform field, could be used for an improved 180° separator was first recognized by H.O.W. Richardson [56]. He also found that under suitable conditions both lateral and longitudinal focusing could occur. The idea was then further developed by O. Kofoed-Hansen, J. Lindhard and O.B. Nielsen, who in particular discussed the case where both source and focus are placed outside the magnetic field [57]. Finally, a magnet producing a field with a $1/r$ dependence is used in the S-2 separator at Arzamas-16, thus confirming that high productivity EMIS is possible with such a field [21].

The various methods proposed between 1940 and 1955 to increase the performance of magnetic spectrometers and electromagnetic separators, and the relative importance of the ideas developed by physicists of different countries with different kind of applications in mind, could be the subject of a study by an historian of sciences. Even a superficial survey of the literature however, would easily point to some of the most important contributions. For example, the general analysis of the double focusing problem by Svartholm and Siegbahn (which led to the 255° method), or the ingenuity of the sector-type separators built by René Bernas. In this context, the six gap "orange" spectrometer of Kofoed-Hansen, constructed at the famous Niels Bohr Institute, was also a clever and rather well known device. It is therefore not surprizing that Jafar must have taken considerable interest in investigating the possibility of using this concept for the separation of the uranium isotopes. In that case, the calutron tanks would have been placed in the air-cored segments, and the optimum size of the magnet would have been of precisely the same magnitude than that of the NA10 magnet.

In practice, the construction of a NA10-like magnet is not a trivial thing. In particular, the windings have to be assembled into coils converging radially to the axis of the magnet. The problem is then one of assembly because the coils cannot simply be wound and later fitted together with the iron pieces: the coils have to be made by wrapping the windings around the steel once the full magnet carcass has been assembled. The solution was to make the coils by using a sophisticated high frequency welding technique to join copper bars. This implied the resolution of a number of ancillary problems, such as the electrical insulation of the coils, etc.

In conclusion, even though a multitank calutron concept based on the NA10 magnet is attractive in theory, it leads to a number of engineering problems which

would certainly have been considerable for Iraq. In fact, Jafar ultimately settled on another design, based on the 255° concept, which in one respect has some similarity with the original NA10 proposal, i.e. the use of magnetized cylinders of steel [53]. Such magnets are much easier to build and were in fact used in another CERN experiment, NA4.

2.4 Iraq's calutron design

Because of the rather limited amount of reliable technical information published until now, it is still not possible to give a truly accurate technical description of the Iraqi attempt to produce highly enriched uranium by means of calutrons, and to make a well documented independent assessment of this effort. The only non-classified first hand information on the subject are the reports to the UN Security Council on the fifteen IAEA on-site inspections under Security Council resolution 687 (1991) of Iraqi nuclear capabilities, carried out between May 1991 and November 1992. A number of photographs and articles by members of the UN inspection teams have also been released by the IAEA over the same period of time. In this section, using at best these documents, we will try to describe the scientific principles of the specific calutron design developed by Iraq. To keep our discussion at the level of the scientific principles, and due to the fragmentary nature of the available information, we will not address the many technical details that would be discussed in a comprehensive assessment.

The central piece in any electromagnetic isotope separation system is the magnet which provides the mass analysing field. It is therefore fortunate that precise information is available on the magnet used by Iraq. Engineering drawings of the steel part of this magnet have been published [58,59] and several good photographs are available [59,60].

The distinctive feature of Iraq's calutron design is the use in an industrial-scale separation facility, of an axially symmetric magnetic field with the right kind of non-uniformity to produce double-focusing of the ion beam [7]. Such a field had been used for example, in the calutron built by Artsimovitch et al. in 1958 [20], and was recognized by the French in 1965 to "offer considerable advantage as regards better focusing and increase of the transmission yield, allowing separation of more intense beams with a good enhancement factor and yield" [26,27].

In order to have a multi-calutron configuration in which the separation tanks are placed in between adjacent magnets to utilize the magnetic field more economically, a special modular design is necessary. In Iraq's case, the basis of this design

is a rotational symmetric dipole magnet shaped as a truncated flat double cone with a slope of about 8^{o} (Fig.5). For the first enrichment stage (i.e. the alpha-process) the outer radius of the magnet is about 220 cm and the maximum thickness about 70 cm. For the second enrichment stage (i.e. the beta-process) no drawings are available. It is known however, that the magnet was similar in shape but half the size.

The general arrangement of the magnets and interleaving separation chambers is known from the first three IAEA inspections [61,62] and an Iraqi letter commenting on the third IAEA inspection [63]. Iraq's first industrial-scale EMIS facility was constructed in Tarmiya, 40 kilometers northwest of Baghdad. A second facility was planned at al Sharqat, 200 kilometers northwest of Baghdad. The two plants were to be identical with a total of 70 alpha-calutrons and 20 beta-calutrons in each. The 70 alpha separators were to be installed in two large (5 m by 60 m) parallel piers [61, p.11] with 35 separators in each line. This gives an average space of 170 cm per separator. Removing 70 cm for the magnet width, a space of about 100 cm is left for the vacuum chamber. At the end of each line, a half magnet provides an end-pole. Interconnecting the end-poles of both lines with iron plates, the magnetic flux can be closed and the resulting configuration is similar to the "race-tracks" built in Oak Ridge during World War Two. A schematic of this arrangement is shown in Fig.6. The same basic principles were to be used in the beta separators, with everything scaled down by a factor of two. While the alpha ion-beam mean radius was 120 cm, the beta ion-beam mean radius was 60 cm.

From the shape of the dipole magnet, Fig.5, and the configuration depicted in Fig.6, it is possible to discuss the main properties of the mass analysing field system used in Iraq's calutrons. Good focusing requires very accurate fabrication of the pole-pieces in order to obtain exactly the required field form. In Iraq's case, the problem of fabricating a number of large magnets with complicated non-linear pole faces has been avoided by using dipole magnets with simple conical pole-pieces. A sufficiently precise knowledge of the field form can then be gained from the simplified second order analysis of Snyder et al. [64, p.854]. In this approximation, the field in the midplane between two pole faces is described by a field-index n which is a function of the slope of the pole-pieces, the beam radius and the spacing between the two pole faces. In particular, $n = 0$ for a uniform field, and $n = 1/2$ for the Svartholm-Siegbahn field of the 255^{o} method. With Iraq's calutron magnet and the configuration of Fig.6 in which there is room for a 90 cm separation chamber, the field index is about $n = 1/4$. Iraq's choice for the alpha-separator field form is therefore a compromise between those for the 180^{o} and 255^{o} methods.

The compromise is a trade-off between productivity and quality. The larger

the space between the magnets, the more room there is for the ion-beams in the separation chambers. For a given number of magnets, this increases the output, but at the expense of the enrichment of the product.

On one hand, if the greatest possible enrichment is desired, the field form required is that of the 255° method, which is obtained when the minimum spacing between the magnets is only 30 cm. This leaves just enough room for a 30 to 60 cm wide vacuum chamber. In such a chamber, it is difficult to use more than one or two beams. In effect, to generate an intense beam, the ion current is usually extracted from the source through a narrow slit, about 10 to 40 cm long. The source assembly is thus at least 20 to 50 cm wide, not much less than the width of the separation chamber itself. To have more than one beam, the ion-sources must be put below one another. This possibility, investigated by the French in the 1960s, is in practice limited to two concentric beams with two different radii [26]. The reason is that when beams from several independent sources overlap the system becomes unstable and the failure of one beam can cause all the beams to fail.

On the other hand, if a lower enrichment is acceptable an increase in productivity is possible by widening the space between the magnets. This allows the use of wider sources (i.e. with a longer extraction slit) or the use of several ion-sources positioned side by side. For example, with a spacing of 100 cm, there will be room for two or three double-sources, i.e. as many as six ion-sources in one 90 cm thick vacuum chamber. With this spacing the field index takes a lower value (1/4 instead of 1/2) and the benefits of the non-uniform field become less significant resulting in lower enrichment of the output. According to the theory [7], the optimum focusing angle also decreases from 255° down to about 210°. The widening of the gap between the magnets would in principle require a redesign of the vacuum chambers. Such a modification was eventually not necessary to achieve a sufficiently enriched product in the first-stage separation units. That this interpretation is plausible is supported by the photographs shown in Fig.7.

In Fig.7a, an alpha calutron chamber is seen on its side. Assuming a diameter of 440 cm its thickness is about 90 cm. The upper side is on the left, with two protrusions on each side of a hook. The bottom side is on the right with two ports that may have been connected to the vacuum pumps. The angle between the two upper protrusions is close to 255°, and each of them has three axially directed rectangular channels that may have contained one double ion-source or one ion-collector assembly. That Iraq's calutron could have had two to six sources has been reported in at least one publication [65, p.18].

In Fig.7b, a beta calutron chamber can be seen. Assuming a diameter of 200 cm, its thickness is about 30 cm. Nothing definite can be said concerning the focusing angle, but it is most likely that the beta calutrons used the 255° method

to achieve the higher separation power required by the second enrichment stage.

In conclusion, having used the engineering drawings of the magnet and the published photographs as the main input, our analysis is summarized as follows. The basis of Iraq's design is not the 180^{o} method used during World War Two but the 255^{o} method. For that purpose, a dipole magnet with a 8^{o} conical shape was built for the first enrichment stage. Using a 30 cm vacuum chamber, the 60 m long process bay of the Tarmiya plant could have accommodated a maximum of 120 magnets and 120 concentric double-beam separation units operating in the 255^{o} mode. Since the first-stage enrichment did not require the full separation power of the 255^{o} method, it must have been decided to put only 70 magnets in the process bay. The advantage is that substantially fewer magnets are required, freeing enough room for $70 \times 3 = 210$ double-beam units, and therefore increasing throughput by a factor of 210/120 . This conclusion is independent of the specific assumptions made here, i.e. the use of double ion-sources with non-overlapping beams [26]. It is not impossible that Iraq's calutrons had multiple-beam ion-sources in which several extraction slits, with lengths of the order of 90 cm, were placed just below on another to produce two or more overlapping beams of similar radii.

As previously explained, a comprehensive assessment capable of answering whether or not the Iraqi effort was close to producing enriched uranium in significant amounts, would have required the detailed analysis of many other important aspects such as Iraq's ion-source technology. According to the IAEA inspection reports [62, p.6], and consistent with experience elsewhere in the world, Iraq found that the only real obstacle in the development of an efficient EMIS system is the design of a good ion-source. This is probably why the alpha calutrons under installation when the Gulf War began, had only four 150 mA ion-sources in each separation tank. Assuming an availability of 55%, a straight-forward calculation shows that the maximum theoretical production of Tarmiya would have been about 14 kilograms of U-235 per year, in the form of 12 and 90% enriched uranium, for the first and second enrichment stage respectively [63].

2.5 The difficulties of publishing

In 1980, two years after receiving a PhD in physics, Gsponer left elementary particle physics and stopped working at CERN. His aim was to establish a *scientific* research institute in which himself and other researchers could apply their professional skills to the analysis of important disarmament problems. Together with Roy Preiswerk, then Director of the Institute of Development Studies of the

University of Geneva, GIPRI, the *Geneva International Peace Research Institute*, was created. An association whose most active members were physicists and social scientists, primarily from CERN and the University of Geneva, and several prominent local political figures.

GIPRI's initial research program concentrated on the military applications of particle accelerators. The idea was to include the military impact of particle accelerator technology, of which calutrons are an example, in the arms-control/disarmament debate and to provoke a discussion in the scientific community on the subject.

The third review conference of the Non-proliferation Treaty (NPT) was to be held in Geneva in August 1980. This presented a good opportunity to publish a paper and so the first GIPRI report was written for the occasion. The title was "Particle accelerators and fusion technologies: implications on horizontal and vertical proliferation of nuclear weapons". The draft of this paper [1] had five chapters, the first one on enrichment. This chapter, after reviewing various methods, concluded with the following paragraph on EMIS:

> "Finally, the oldest enrichment method (which has the capability to achieve an almost complete separation of U-235 in a single step), i.e. *electromagnetic isotope separation*, may become interesting in special circumstances thanks to technological advances. In effect, while this method is relatively expensive and economically unattractive, it uses only well known classical technologies. These technologies (ion sources, vacuum, large magnets) are routinely used in nuclear physics and are certainly within reach of many countries. The construction of an enrichment plant based on this method (of the kind the United States built during World War Two) could however, hardly be justified for civilian purposes and would be very difficult to conceal. Nevertheless, the appeal of this enrichment method is illustrated by the fact that Iraq recently showed strong interest in the technology of large magnets" [1, p.3].

The other chapters dealt with the following subjects; accelerators for fissile material production, application of accelerators to nuclear weapons technology, thermonuclear fusion and hybrid reactors, applications of inertial confinement fusion to nuclear weapons technology and finally, implications of emerging nuclear technologies for developing countries.

Obviously, at a time when the debate on the risk of nuclear weapons proliferation was centered on problems arising from nuclear power generation by means

of fission reactors, an article with such a vast content was extremely ambitious. Despite efforts to keep the content as simple as possible, the average reader would have had some difficulty understanding the numerous technical concepts involved. In addition, Gsponer was a totally unknown young physicist and did not have the authority necessary to present new ideas to the rather closed and conservative arms-control/disarmament community. This lack of authority was particularly detrimental because the paper stressed a number of conclusions Gsponer was able to draw using scientific deduction alone. It also included a statement on Iraq's interest in EMIS technology for which there was no reference because Gsponer had accidentally discovered the fact himself.

Consequently, having given the draft for comment to several scientists and researchers in the field of disarmament, Gsponer decided to shorten the paper. The first and last chapters dealing with enrichment and the implications for developing countries were removed. The paper was simplified by narrowing its focus on the nuclear proliferation aspects of accelerator and fusion technologies, and avoiding the danger in publishing something new and crucial on Iraq's nuclear ambitions. The years 1979-1981 were marked by a number of violent incidents in which Israeli secret services and armed forces attempted to halt Iraq's efforts to acquire nuclear reactor and reprocessing technology. It was a serious concern therefore, that mentioning Iraq's definite interest in calutron technology could endanger Gsponer and former CERN colleagues.

The abridged paper was finalized with the help of Bhupendra Jasani, a physicist working at the *Stockholm International Peace Research Institute*. It was sent to the heads of delegations of the 1980 NPT review conference [2]. Later it was submitted to *Science*, *Technology Review* and *The Bulletin of the Atomic Scientists*. All three journals rejected the paper. Once translated and printed in German and Italian Gsponer did not continue to try to find an English publisher.

In the Spring of 1981, soon after Ruth Adams was elected Editor of *The Bulletin of the Atomic Scientists*, she made a tour of Europe visiting several disarmament research institutes to encourage European researchers to submit articles to the *Bulletin*. The idea was to open the journal to broader perpectives than the American ones which had dominated the journal since its foundation in 1945. In Geneva, Adams visited GIPRI where Gsponer told her about his research on the military use of particle accelerators. Interested by the subject, she invited him to submit a short paper on a recent public debate in which the particle accelerator issue was raised in the context of the construction of LEP, a very large particle accelerator to be built at CERN. The result of the peer review was negative. On the advice of Frank Barnaby, Director of SIPRI in Stockholm and an Editorial advisor of the *Bulletin*, Gsponer submitted a new version of the paper in February 1982. In

March, he received copies of the proofs of the paper scheduled as a commentary for the May 1982 issue of the *Bulletin*. Notwithstanding this approval and that he had corrected and returned the proofs, his commentary was never printed. Despite several attempts, there was never any answer from the *Bulletin* to any of his letters enquiring as to why the commentary had not been printed.

Had Gsponer's commentary been censured? Had his paper addressed sensitive issues which were not supposed to be discussed in non-classified literature? The only paragraph that could have justified such an action is as follows:

> "Elementary particle physics, at the forefront of fundamental research, is mainly carried out through the use of increasingly powerful and larger high energy accelerators and storage rings. For applications of accelerators requiring lower energies but very high currents, the advances are equally impressive. These developments are leading towards numerous new applications, especially in the fields of nuclear energy and weaponry. Particle accelerators are becoming usable for efficient breeding of fission and fusion materials, for driving inertial confinement fusion devices, for studying the physics of thermonuclear weapons, and so on. The concept of high energy particle beam weapons may become feasible and free-electron lasers using electron accelerators and storage ring technologies may provide a new generation of highly efficient and powerful lasers with many military applications" [66].

Of course, it is not possible to know if the commentary was censured for classification reasons or not. The only thing that can be said for sure, is that this kind of problem is a recurring one in the United States [67,68].

Another less dramatic explanation for the censorship of Gsponer's commentary is that nuclear physicists working in non-military laboratories, and especially those using particle accelerators, are extremely nervous when it comes to the question of the military impact of their work. The origin of this irascible response can be found in the passionate desire of many atomic scientists to believe that their work has many more positive consequences, such as nuclear energy or a better understanding of the fundamental laws of nature, than terrifying consequences such as nuclear weapons.

In 1982 Gsponer left GIPRI to create ISRI, the *Independent Scientific Research Institute*. It was a much less ambitious enterprise than GIPRI, concentrating on the independent assessment of nuclear technologies. For instance, in a paper

presented at the Third International Conference on Emerging Nuclear Energy Systems, Gsponer and others stressed again the nuclear proliferation impact of new technologies [3]. In particular, in a section on enrichment, (with the electromagnetic, plasma and laser separation processes in mind) they warned that

> "new technologies could completely change the situation prevailing since 1945, namely, the fact that enrichment facilities are in general much larger, more complicated and expensive than simple production reactors" [3, p.172].

Similar concerns about the impact of particle accelerator technology on enrichment were repeatedly expressed in *La Quadrature du CERN*, a book Gsponer had written with others for CERN's thirtieth anniversary [47, p.20; 60; 70-73].

In 1990 Gsponer was in Mauritius. Like most, he followed the Gulf War events on the radio and television. He resumed his work on theoretical physics once military action was over.

Gsponer had heard the alarming statements that Iraq might have been working on an atomic bomb. But at no point did he think that they could have made much progress otherwise it would have been known for a long time. It came as a terrible shock to him to learn about Iraq's use of calutrons from a *New Scientist* article published in July 1991 [69].

More than 12 years had passed since Gsponer had discovered Iraq's interest in calutrons. An event that he was trying to forget. As with his evaluation of particle beam weapons research [70,71], he thought more and more that his appreciation of this discovery was possibly exaggerated, and that he had been wrong to quit his work as a particle physicist. After all the negative comments about his work on the military implications of particle accelerator technology, and the personal attacks he had endured from former friends and colleagues, a tragic event — the largest military coalition since World War Two — finally confirmed that his worries were well founded.

The time had finally come to make public how Gsponer had discovered in 1979, Iraq's work on EMIS technology. For obvious reasons, in all his publications, he had never explicitly mentioned Iraq. After the Gulf War however, there was no reason for further caution. Since he was still in Mauritius, he had first to return to Geneva to meet former CERN colleagues, and then to wait for a good opportunity.

In 1995, Gsponer thought that the fifth review conference of the NPT would be an appropriate time to put straight the historical record on Iraq's calutron program. Having investigated the possibility of publishing a report on calutron technology

to be sold or used as the basis of a book, he went to New York to inquire whether the *New York Times*, with the help of some personal contacts in the science section, would be interested in the story. These attempts were unsuccessful. Meanwhile, a Geneva based science journalist picked up the story and wrote an article for the *Journal de Genève*, a daily newspaper with a good international audience. After double-checking the facts, and interviewing Freudenreich to clarify the circumstances of the 1979 visit to CERN by an Iraqi engineer, the article was published as the main news story of the 22-23 April weekend edition of the journal [72], one week after the NPT review conference in New York had started.

Except for some emotional reactions from the CERN staff and management, the impact of the *Journal de Genève* article was minimal, especially on the NPT negotiations in New York. Its main merit was therefore to publish an important historical fact, and to highlight the blindness of the scientific community with regard to the military implications of its activities.

Fifteen years after Gsponer's report for the 1980 NPT review conference was written, the nuclear weapon states are coming close to an agreement on a Comprehensive Test Ban Treaty (CTBT). While this treaty would forbid all nuclear tests, either above or under ground, the nuclear weapon states, the US and France leading the way, are starting to build very large inertial confinement fusion facilities [73]. These facilities enable the detailed study of the ignition process of thermonuclear explosions. The irony is that the aim of Gsponer's papers of 1980-83 [1,2,3], was precisely to show that such a treaty would be meaningless if accelerator and fusion technologies were systematically applied to the development of new nuclear weapons. With these technologies it is indeed possible to conceive and test new weapons in the laboratory without large scale explosions.

Chapter 3

Implications for the proliferation of nuclear weapons

3.1 Beam technologies and nuclear weapon proliferation

Enrichment of fissile materials by means of calutrons is a classical example of the use of particle beam technology in the nuclear fuel cycle. Another example is breeding of special nuclear materials by means of particle accelerators. The current interest in these technologies is due to the fact that *beam technologies* are becoming increasingly competitive substitutes for traditional nuclear technologies. Laser and particle beam technologies are also key components of emerging nuclear energy systems such as fusion, and of increasing importance for the qualitative development of nuclear weapons.

In the early eighties when Gsponer and his GIPRI/ISRI collaborators were stressing the nuclear proliferation risk of "old" technologies such as EMIS, their opinion was at odds with the generally accepted one. For instance, in an excellent review on uranium enrichment and nuclear weapon proliferation [5], despite the recognition that electromagnetic processes were "again under serious consideration" [5, p.186] the general conclusion was to consider the calutron as "no longer a viable process" for the production of enriched uranium [5, p.22]. Today, after Iraq's construction of a large EMIS plant, the question is not so much which assessment was right or wrong, but why Iraq's enormous effort remained "undetected" until the end of the Gulf War. This is particularly disturbing because all analysis have concluded that the construction of an industrial-scale EMIS plant would be

very difficult to conceal, and because Iraq's motivation of using the EMIS process was precisely the same as the motivation of the United States during World War Two, to produce fissile material for a nuclear weapon by all means and at any cost.

In this context, it should be stressed that besides EMIS, other proliferation-prone "old" technologies should be given serious consideration [1,2,3]. Of these technologies, the most important one is certainly that of particle accelerators. In fact, from 1941 (when plutonium was first produced) until the end of 1943, circular accelerators were the sole source of plutonium, and over this period slightly more than 2 milligrams of plutonium were produced [2]. It has been calculated that a 1000 MeV proton accelerator with a beam of 1 mA (i.e. a beam power of 1 MW) could produce enough spallation neutrons to breed about 10 kg of plutonium per year, enough for two to four atomic bombs [3]. The construction of such an accelerator, and of the associated reprocessing plant, is certainly possible for many countries, including some in the developing world. Compared with a calutron plant of similar fissile material output, the cost would be considerably less. A major obstacle to the acquisition of such a technology is that, contrary to nuclear reactors, complete accelerators with the requisite characteristics cannot be bought on the market. Similarly with what Iraq had to do in the case of its calutron plant, an accelerator-breeder would have to be built by assembling it from its components, something that requires a considerable indigenous research and development effort. In practice, the main difference would come from the fact that particle accelerator technology is in several respects more sophisticated than calutron or even centrifuge technology. With the current proliferation of advanced scientific, industrial and military technology, this kind of barrier is likely to become less and less effective in the future.

Of special concern is the fact that particle accelerators have recently established themselves as very serious candidates for replacing aging nuclear reactors in many kinds of military and/or civilian applications. For a given total thermal power, a major technical advantage of spallation based systems is that productivity (i.e the number of neutrons or the amount of plutonium or tritium produced) is roughly five times greater than the productivity of fission based systems [2]. As a result, the problems of radioactivity, containment and cooling will be proportionally smaller by about the same factor.

In the field of neutron physics research, the current problem in Europe [74] as well as in the USA [75], is the replacement or upgrading of aging reactor or accelerator facilities. In Europe, there is a proposal to replace an old German research reactor fueled by highly-enriched uranium with a spallation neutron source (based on a 5 MW beam-power accelerator) rather than replacing it by a new research reactor of the same type [75]. Such a switch from a reactor to a different type

of neutron source has a positive non-proliferation impact, mainly by suppressing the risk of diversion or theft of highly-enriched uranium. The negative impact is that it will contribute to the spread and development of accelerator-based neutron generation technology.

The most significant development however, is the US proposal to replace its military production reactors with accelerator-based facilities [76]. The possibility that the US will build a giant tritium-producing accelerator (with a 100 MW beam power), dubbed the APT, Accelerator Production of Tritium, is quite high, since it could simultaneously satisfy the needs of both military and scientific communities. In the words of Burton Richter, the Director of the Stanford Linerar Accelerator Center: "With small modification to the APT, the U.S. can have both the world's premier neutron source and a secure tritium supply" [76]. If the US goes ahead with this proposal, the road will be open for other countries to follow. Of direct concern would not only be the declared nuclear powers, but also countries like India or Japan, which already have substantial knowledge and skills for building accelerators and existing or projected spallation neutron sources [2,3].

Another recent development is the proposal to use accelerators to incinerate long lived radioactive waste [77]. Since the transmutation process is producing a large number of spallation neutrons, the same technology could be used to breed plutonium or tritium [77].

Finally, while the idea was not new, Carlo Rubbia, Nobel laureate and at the time Director of CERN, unveiled in 1993 a "method to produce safe and clean nuclear energy by aiming accelerated protons at a thorium target" [78]. The method claimed to pose "no risk of military proliferation", and to be "most advantageous for developing countries". Since then, experiments were performed at CERN [79] and research is underway to investigate the possibility of using the system as an incinerator of radioactive waste. While the method may have some potential technical advantages, it must be stressed that its nuclear weapons proliferation impact is far from negligible.

Since accelerator based power systems may lead to economically attractive designs with an electric output of about one tenth of a normal nuclear power station, the problem of safeguarding a large number of dispersed accelerator power plants will be considerable. Similarly, in case of the clandestine use of accelerator technology to breed plutonium or tritium, the problem of detecting the illicit activity will be magnified by the five fold reduction of heat and radioactive effluents. The main proliferation problem however, is the fact that the construction of any kind of accelerator system for commercial scale nuclear power generation, nuclear fuel generation for civil or military use, transmutation, etc, will open another Pandora's box of problems that can only exacerbate the current nuclear proliferation

situation.

3.2 EMIS for plutonium purification

It is well known that the kind of plutonium bred in commercial power-generating nuclear reactors is not suitable for the design of reliable nuclear weapons. The nuclear weapons in the contemporary military arsenals are made of weapons-grade plutonium, i.e. plutonium that is more than 95% pure in the isotope Pu-239. A state determined to make nuclear weapons using reactor-grade plutonium (i.e. containing between 10 to 30% of the unwanted Pu-240 isotope) would certainly first try to purify it to convert it into weapons-grade plutonium. This would simplify considerably the design of the weapon by enabling the use of less sophisticated implosion technique to achieve criticality.

In theory, the isotopic separation of plutonium is a much less demanding task than enrichment of uranium. For instance, as the initial Pu-239 content of reactor-grade plutonium is over 70%, while the U-235 content of natural uranium is only 0.7%, a plutonium enrichment plant will be about 100 times smaller than an uranium enrichment plant of the same fissile material output. For example, a straightforward calculation shows that using the electromagnetic separation method, a single calutron with a beam current of less than 100 mA is sufficient to produce 5 kilograms of weapons-grade plutonium per year.

The technology of plutonium isotopic separation however, is no more covered by secrecy than uranium enrichment technology. An important reason for this is that nuclear reactor research, as well as nuclear weapons diagnostic [80], requires plutonium isotope separation in order to measure Pu-240 relative to Pu-239 production because these isotopes have alpha-decay energies very close to one another. In practice however, there are problems.

First, any method suitable for separating kilogram quantities of pure Pu-239 from reactor-grade plutonium has to be capable of operating with highly radioactive feed material. For such an application, gaseous diffusion or ultracentrifugation for example, are unsuitable because the whole apparatus (including key components such as the porous barriers or the centrifuge rotors) would become highly radioactive so that repair or maintenance becomes impossible. Isotopic separation of radioactive materials requires that the process takes place in a containment vessel which can be removed for decontamination or recovery of the feed material. This is possible with the laser, plasma or electromagnetic separation methods in which the ionized feed material is generally processed within a removable "liner"

enclosed in the vacuum chamber.

Second, the atomic weight difference between Pu-239 and Pu-240 is one, while it is three between U-238 and U-235. Thus, the enrichment of plutonium requires a three fold increase in separation power over enrichment of uranium. This means a substantial increase in difficulty [10, p.348] so that a typical EMIS plutonium separator will look much more like the 255^{o} calutron of Artsimovitch [20] than a World War Two 180^{o} calutron.

A good idea of what a calutron for plutonium separation might look like is given by the S-2 separator of Arzamas-16 [21]. The construction of a facility comprising a number of such calutrons would in some respects be more complicated, and perhaps more costly than the chemical reprocessing plant, which would first of all be required to extract the plutonium from irradiated power-reactor fuel elements. A government having completed the first step would most probably go ahead with the plutonium isotopic purification step, even though it has been proved that by using the appropriate technique, a crude nuclear explosive could be made of power-reactor plutonium [81].

A first country for which it can be seriously argued that plutonium enrichment is a potential nuclear proliferation threat is Iran. Since 1990, Iran has been receiving aid from China for the construction of a small calutron [34]. In 1995, Russia agreed to build a nuclear power reactor on the site of a German reactor which was left incomplete after the collapse of the Shah regime. In a decade or so therefore, and in the case of a breakdown of international safeguards, Iran could have direct access to indigenously bred reactor-grade plutonium, and the potential capacity to turn it into weapons-grade plutonium.

A second country of concern is Japan. Considering the return to Japan in 1993, of more than a ton of Japanese plutonium from a nuclear fuel reprocessing plant in France, Japan's inventory of separated reactor-grade plutonium could reach several tens of tons by 2005-2010. In Japan, the main technical justification for extracting plutonium from spent reactor fuel is its potential use in fast-breeder reactors. There is, however, "the conspiracy theory that in the long term Tokyo aims to develop the capacity to build nuclear bombs at short notice should the international situation so demand" [82]. In such a case, with all its technological might, Japan would certainly not satisfy itself with crude nuclear devices. It is more likely to purify its reactor-grade plutonium in order to build a credible nuclear arsenal. To do so, Japan would be able to chose from the full range of the most sophisticated enrichment technologies, including the laser and plasma isotope separation processes (see section 1.11). Japan's current interest in the development of advanced enrichment technology, and in particular of the plasma separation process (the modern method with the greatest potential in terms of universality and productivity), is of great

concern from the point of view of nuclear weapon proliferation.

3.3 UN resolutions 687 and 707 and their implications for a halt of all proliferation prone nuclear activities

In paragraph 13 of Security Council resolution 687, adopted on 3 April 1991, the IAEA was requested by the Security Council to carry out immediate on-site inspection of Iraq's nuclear capabilities and carry out a plan for the destruction, removal or rendering harmless of items prohibited to Iraq under paragraph 12 of the resolution 687. On 15 August 1991 the Security Council adopted a further resolution, number 707, obliging Iraq to "*halt all nuclear activities of any kind, except for the use of isotopes for medical, agricultural and industrial purposes* until the Security Council determines that Iraq is in full compliance with resolution 707 and with paragraphs 12 and 13 of resolution 687, and the IAEA determines that Iraq is in full compliance with its safeguards agreement with that agency (article 3.vi)".

The plan, and the annexes thereto, which constitute an integral part of the plan, were adopted by the Security Council as document number S/22872/Rev.1. This unprecedented document, drafted with Iraq's specific case in mind, is in fact the first legally binding document in which all activities prone to nuclear weapon proliferation are clearly and comprehensively defined. It is the first time that in an official document, the many ambiguous activities which broadly come under the name of "peaceful nuclear activities", as well as those which are generally considered as non-military scientific research activities, are explicitly recognized as important for the acquisition or development of nuclear weapons. Similarly, by clearly defining those applications of nuclear physics and nuclear energy that are useful for "medical, agricultural or industrial purposes", this document also defines which kind of "peaceful nuclear activities" are really benign from the point of view of nuclear weapon proliferation. In practice, in obliging Iraq "not to acquire or develop nuclear weapons or nuclear-weapons-usable material or any subsystems or components or any research, development, support or manufacturing facilities related to the above" (article 12 of resolution 687), the UN Security Council developed and accepted a document unambiguously defining what in essence is a *nuclear free zone* and created a legal precedent which makes Iraq the first example of such a zone. This precedent is particularly significant because it included the development of procedures and equipments for ongoing monitoring

and verification, which are now applied in Iraq.

While many would object to the idea that resolutions 687 and 707 (or more precisely the plan making Iraq a nuclear free zone and thus a de facto nuclear weapon free zone) could be applied to or adopted by all nations, this idea merits much consideration in the light of the danger that nuclear weaponry represents for the world.

Annex 1 of document S/22872 defines activities prohibited or permitted under resolutions 687 and 707. It is completed by Annex 3, a fifteen page long list of all items specifically prohibited, or may be prohibited if used in prohibited activities, and by Annex 4 which details permitted activities. Significantly, Annex 1 and Annex 3 are much more explicit and comprehensive than any previous official documents listing equipment and materials subject to nuclear export controls, including the so-called "Zangger list" [83]. Considering the importance of these annexes for future discussions on nuclear weapon free zones and an eventual nuclear free world, Annex 1 is reproduced in the Appendix.

A salient feature of Annex 1 is that it makes a clear distinction between activities prohibited by Resolutions 687 and 707. Activities prohibited by resolution 687 (paragraphs 2.1-2.9 of Annex 1) are those which are clearly prohibited to non-nuclear-weapon states by the Non-proliferation treaty and those constituting a direct short-term nuclear weapon proliferation threat in case of diversion or misuse, and therefore put under IAEA safeguards.

The prohibition of nuclear activities by Resolution 707 (paragraphs 2.10-2.18 of Annex 1) is much more comprehensive; it comprises all possible nuclear activities except applications of isotopes to agriculture, industry and medicine. While the activities put under IAEA safeguards are essentially those related to nuclear power generation by means of fission reactors, Resolution 707 prohibition extends to *nuclear fusion* based on magnetic or inertial confinement (paragraph 2.15), *production of isotopes* of any kind (paragraph 2.16) and *particle accelerators* of all types (paragraph 2.17).

In other words, Resolution 707 is a legal implementation of the suggestions made in 1980 that international safeguard measures should be extended to particle accelerator and fusion technologies [1,2,3], and an explicit recognition of the fact that these technologies constitute a direct threat for nuclear weapon proliferation.

A second important feature of Annex 1 is that it prohibits not only "design, manufacturing, import of systems, equipment and components, pilot plant construction, commissioning and operation, or utilization", but also "research and development" on the specified activities. This is a very important novelty because, until Resolutions 687 and 707, research and development activities have always

been excluded in arms control agreements [84]. In the case of the future Comprehensive Test Ban Treaty, only a very limited range of research activities, i.e. those in which a *fission* chain reaction is started, will be prohibited. In particular, there will be no prohibition on thermonuclear fusion, including inertial confinement fusion, even though such research is ultimately motivated by the possibility of triggering large scale thermonuclear explosions without needing a fission primer. The potential of inertial confinement fusion for studying thermonuclear weapons physics and effects has been discussed in open literature since 1975 (see [2,3,84] and references therein).

The necessity of arms control and disarmament measures at the research and development stage has been repeatedly stated albeit but by a few [3,47,84,85,86], in contradiction with the prevailing opinion in the scientific community [87]. These measures should constrain both "civilian" and "military" research activities, including fundamental research as it was deemed necessary for example, in the case of antimatter [86]. In the instance of a ban of inertial confinement fusion research, the construction of very large laser facilities for fundamental research in astrophysics, hydrodynamics, high-pressure physics or plasma physics [88] would be forbidden.

3.4 Intelligence failure or staging for counter-proliferation?

Until now, the most comprehensive coverage of Iraq's nuclear weapons program is provided in a series of articles by David Albright and Mark Hibbs in *The Bulletin of the Atomic Scientists* and *Arms Control Today*. These articles also provide a good introduction to some of the most disturbing problems relating to Iraq's case, such as the question of the "intelligence failure" and the prospect of a "counter-proliferation" policy replacing the current non-proliferation regime. A proper assessment of this "failure" is essential precisely because it is often quoted today in the context of either proliferation and nuclear terrorism [89] or counter-proliferation [90].

On the intelligence failure question, Albright and Hibbs' opinion in 1992 was categoric:

> "After the Osiraq bombing, Iraq simultaneously pursued several means of producing highly enriched uranium. Postwar revelations of Iraq's most developed enrichment route, based on archaic calutron

> electromagnetic separation technology, startled the world. Western intelligence agencies had been fully aware that Iraq was attempting to develop the means to enrich uranium, but had focussed on the gas centrifuge effort — which matched current approaches used in several developed nations — and missed the calutron effort completely" [Ref.91, p.5].

In 1993 however, Albright's opinion was somewhat more cautious:

> "Iraq is considered an intelligence failure because large-scale nuclear activities were not discovered by the IAEA or Western intelligence agencies" (before the end of the Gulf War). The reasons for this failure, however, involve more than a deficiency in either safeguards or intelligence collection methods.
>
> Western governments did not aggressively pursue leads about Iraqi nuclear efforts or seriously impede Iraq's nuclear program during the 1980s. (...)
>
> Despite a failure to detect the full scope of Iraq's program, intelligence agencies knew enough before the Iraqi invasion of Kuwait to have justified some sort of intervention. (...)" [Ref.92, p.15].

It can safely be assumed that there are inconsistencies between what was known to Western intelligence agencies and what was done with that information. This was highlighted in the response of IAEA officials to international media criticism of the IAEA when Iraq's nuclear weapons program was uncovered. Jon Jennekens, retired Deputy Director General for Safeguards of the IAEA, in his first public statement since retiring, said for instance:

> "The Americans and the British knew what (Saddam) Hussein was up to because they pulled a sting operation when the Iraqis were trying to import very high-precision timing devices from the U.S., through the U.K. They pulled a sting operation and arrested people so it was clear why the Iraqis wanted these instruments, but the information was never divulged to the IAEA secretariat" [93].

In fact, the whole process which after the end of the Gulf War led to the uncovering by IAEA inspectors of the details of Iraq's nuclear weapons program, can be seen as a cover-up operation. One in which the IAEA was used to hide the extent of the knowledge that Western intelligence had already obtained before the

war. For example, is it credible that it was only on the basis of information provided by two defectors, that the most important discoveries about Iraq's nuclear weapons program were made? Firstly, in June 1991, a defector provided the information that led to the huge facility in which uranium was enriched with calutrons. Secondly, in September 1991, another defector informed Western intelligence on the location of 25'000 documents. These included design information definitely confirming that research and development in several key areas specifically related to nuclear weapons had been done in Iraq [94].

Moreover, it is difficult to believe that Iraq's enormous nuclear effort had remained undetected for so many years, an effort which cost over 10 billion dollars during the 1980s and employed 10'000 or more scientists, technicians and others. It is improbable that only a few isolated individuals like Gsponer, were aware of Iraq's long time interest in calutron technology. There are also several hints indicating that the full extent of Iraq's effort was already known before the Gulf War. For instance, this knowledge would certainly have been necessary to convince some countries to join or accept operation 'Desert Storm', and President Bush's repeated suggestion before the war, that Iraq's bomb was only months away [95].

A possible explanation of these events could be that from the early 1980s there was a gradual shift from a *non-proliferation* to a *counter-proliferation* policy [90,96,97]. If this is so, the lessons of Israel's precedent, the bombing of Osiraq in 1981, must have been taken into account.

The bombing of Osiraq by the Israelis took place when the reactor was almost ready to produce plutonium. By comparison, Iraq's pilot calutron plant started in 1981. Assuming that intelligence services knew this, counter-proliferation action would still have been difficult from a political point of view. The military significance was not sufficient at the time: it was a small experimental facility.

The installation of the first large alpha calutrons in the Tarmyia production plant only started in 1989. Not until 1989-1990 therefore could Israel or the USA have begun to put political or military pressure on Iraq: a counter-proliferation policy needs a clear cut proliferating situation in order to justify intervention. Otherwise the political cost, which was quite high in Israels' precedent of 1981, would be prohibitively high.

But Iraq invaded Kuwait in August 1990. Was this invasion encouraged by Saddam Hussein's belief that he was very close to having the atomic bomb in his hands? Was this just the kind of mistake the Western powers were waiting for in order to neutralize Iraq's growing military strength? Were the Western powers expecting such a mistake and did not intervene earlier by political or economical

means because of a shift from non-proliferation to counter-proliferation? This would explain why Iraq was allowed to come so close to having an atomic bomb.

In any event, 1991 was not only the year of the Gulf War — which could be seen as the first major act of counter-proliferation — but also the year in which France and China finally joined the NPT. An event that paved the way to the unconditional permanent extension of the NPT, decided in New York in 1995. Not all the motivations of France and China to join the NPT are known, but it may well have been that the assurance that deliberate force could be legitimized to keep nuclear weapons in the hands of the superpowers, must have been an important one. In declaring on the 31th of January 1992, that the *proliferation* of weapons of mass destruction was a threat to international peace and security, the Security Council has in effect authorized the use of force against any proliferating state, including those which are not party to any international treaty.

References

[1] A. Gsponer, Implications des nouvelles technologies pour la prolifération horizontale et verticale des armes nucléaires, 16 juillet 1980, unpublished.

[2] A. Gsponer, Particle accelerators and fusion technologies: Implications on horizontal and vertical proliferation of nuclear weapons, GIPRI-80-03 (1980) 23 pp. Report distributed to the Heads of delegation to the 1980 NPT Review Conference. Translation of Implications des technologies de la fusion et des accélérateurs de particules sur la prolifération horizontale et verticale des armes nucléaires, GIPRI-80-02 (1980). Unpublished in French and English. Translated and published in German and Italian:

A. Gsponer, Teilchenbeschleuninger and fusionstechnologien: Schleichwege zur atomaren Rüstung, Scheidewege 11, No 4 (1981) 552-566. Reprinted in Die Erde weint - Frühe warnung vor der Verwuüstung (DTV/Klett Cotta, Munich, 1987) 48-62.

A. Gsponer, Gli acceleratori e l'atomica, Sapere (Ottobre 1982) 9-14.

[3] A. Gsponer, B. Jasani and S. Sahin, Emerging nuclear energy systems and nuclear weapon proliferation, Atomkernenergie/Kerntechnik 43 (1983) 169-174.

[4] For an introduction to laser methods of uranium isotope separation, see C.P. Robinson and R.J. Jensen in Uranium enrichment, Topics in Applied Physics, Vol 35 (Springer Verlag, Berlin, 1979). For a status report on the AVLIS process, see M. Campbell, Energy and Technology Review, Lawrence Livermore National Laboratory, (January-February 1995), 24-25. For an assessment of laser enrichment and non-proliferation, see R. Kokoski, Laser isotope separation: technological developments and political implications in SIPRI YEARBOOK 1990 (Oxford University Press, Oxford, 1990) 587-601.

[5] For an introduction to the plasma separation (or ion resonance) process, see A.S. Krass et al., Uranium enrichment and nuclear proliferation, (Taylor and Francis Ltd, London, 1983) 179-283.

[6] R.K. Wakerling and A. Guthrie, Ed., Electromagnetic separation of isotopes in commercial quantities, report TID-5217, June 1949, Classification cancelled April 15, 1955.

[7] N. Svartholm and K. Siegbahn, An Inhomogeneous Ring-Shaped Magnetic Field for Two-Directional Focusing of Electrons and Its Application to b-Spectroscopy, Arkiv. Math. Astron. Fysik, 33A, No 21 (1946), 1-28. idem, No 24 (1946) 1-10.

[8] For a detailed account of the war-time calutron effort see J.L. Heilbron, R. W. Seidel and B.R. Wheaton, Lawrence and his Laboratory: Nuclear Science at Berkeley, LBL News Magazine, Vol 8, No 3, Fall 1981, pp. 36-41.

[9] D. Hawkins, E.C. Truslow and R.C. Smith, Project Y: The Los Alamos Story, (Thomas Publisher, Los Angeles, 1983) 508 pp.

[10] L.O. Love, Electromagnetic separation of isotopes at Oak Ridge. An informal account of history, techniques and accomplishments, Science, 182(1973) 343-352.

[11] J.G. Tracy et al., Stable isotope enrichment techniques and ORNL separation status, Nucl. Inst. and Methods, B26 (1987) 7-11.

[12] J.G. Tracy, Isotope separation program - present and future, Nucl. Inst. and Methods, A282 (1989) 261-266.

[13] E.P. Chamberlin et al., Status report on the 126^{o} isotope separator construction, Nucl. Inst. and Methods, B26 (1987) 21-24.

[14] M.A. Hilal et al., High uniformity large solenoid for magnetic isotope separation, IEEE Trans. Magn., 24 (1988) 938-941.

[15] D. Holloway, Stalin and the bomb: the Soviet Union and atomic energy, 1939-56, (Yale University Press, New Haven and London, 1994) 464 pp.

[16] I. Golovin, Rossiiskii nauchnyi tsentr-Kurchatovskii institut, unpublished manuscript, 1992.

[17] A. Tikhomirov, Modern tendencies in the enrichment of stable isotopes and their applications in the USSR and elsewhere, Nucl. Inst. and Methods, B70 (1992) 1-4.

[18] V.S. Zolotarev et al., Isotope separation by electromagnetic separators in the Soviet Union, Proc. of the 2nd UN Inter. Conf. on the Peaceful use of Atomic Energy, United Nations, Geneva, Vol. 4(1958)471-479.

[19] Atomic energy for peaceful uses, booklet distributed at the Soviet pavillon

at the exhibition, Geneva, 1958, 68 pp.

[20] L.A. Artsimovich et al., An electromagnetic installation of high resolving power for separating isotopes of heavy elements, Atomnaya Energia, III (1957) 483-491 (Translation, AEC-tr-3160, Oak Ridge, March 4, 1958).

[21] S.M. Abramychev et al., Electromagnetic separation of actinide isotopes, Nucl. Inst. and Methods, B70 (1992) 5-8

[22] S.P. Venovskii and V.N. Polynov, Highly enriched isotopes of uranium and transuranium elements for scientific investigation, Nucl. Inst. and Methods, B70 (1992) 9-11.

[23] J. Koch, editor, Electromagnetic isotope separators and applications of electromagnetically enriched isotopes (North Holland, Amsterdam, 1958) 314 pp.

[24] A.O. Nier et al., Nuclear fission of separated uranium isotopes, Phys. Rev. 57 (1940) 546, 748, 749.

[25] R.H. Bernas and A.O. Nier, The production of intense ion beams in a mass spectrometer, Rev. Sci. Inst. 19 (1948) 895-899.

[26] M. Trahin, Aberrations in a 255^{o} double focusing separator supplied with one and two sources, Nucl. Inst. and Methods, 38 (1965) 121-127.

[27] J. Gilles at al., Design and operation of a 24-inch calutron with several magnetic field configurations, Nucl. Inst. and Methods, 38 (1965) 128-132.

[28] R. Meunier et al., Progress report on separators SIDONIE and PARIS, Nucl. Inst. and Methods, 139 (1976) 101-104.

[29] J. Cesario et al., PARSIFAL, an isotope separator for radiochemical applications, Nucl. Inst. and Methods, 186 (1981) 105-114.

[30] Y. Boulin and A. Jurey, A bench for tungsten crucible crystallization and source outgassing, Nucl. Inst. and Methods, B70 (1992) 12-13.

[31] Hua Ming-da et al., Electromagnetic separation of stable isotopes at the Institute of Atomic Energy, Academia Sinica, Nucl. Inst. and Methods, 186 (1981) 25-33. Li Gongpan et al., Some experimental studies of the calutron ion source, Nucl. Inst. and Methods, 186 (1981) 353-356.

[32] Li Gongpan et al., Current status of the IAE electromagnetic isotope separators, Nucl. Inst. and Methods, B26 (1987) 12-13.

[33] Li Gongpan et al., Electromagnetic isotope separation at the China Institute of Atomic Energy, Nucl. Inst. and Methods, B70 (1992) 17-20.

[34] R. Jeffrey Smith, U.S. worry: Nuclear aid by Beijing to Tehran, Int. Herald Tribune, October 31, 1991, p. 1, p.4.

[35] S.B. Karmohapatro, A magnetic spectrometer for charged particles, Indian J. Phys, 33 (1959) 139-147; A two-directional focusing high-intensity mass-spectrometer, Indian J. Phys, 34 (1960) 407-415.

[36] S.B. Karmohapatro, A simple mass separator for radioactive isotopes, Nucl. Inst. and Methods, B26 (1987) 34-36.

[37] S. Amiel et al., Experiments with the surface ionization integrated target-ion source of the SOLIS, Nucl. Inst. and Methods, 139 (1976) 305-309.

[38] G.D. Lempert and I. Chavet, Mass analysis of milligram samples with the high current isotope separator MEIRA, Nucl. Inst. and Methods, 186 (1981) 1-6.

[39] G.D. Lempert et al., Recent refinements of the separator MEIRA and high enrichment separation results, Nucl. Inst. and Methods, 186 (1981) 13-20.

[40] I. Chavet, Thèse, Université de Paris (1965). See also I. Chavet, Nucl. Inst. and Methods, 38 (1965) 37-40 and I. Chavet and R. Bernas, Nucl. Inst. and Methods, 47 (1967) 77.

[41] M. Fujioka, On-line isotope separator facilities in Japan, Nucl. Inst. and Methodes, B26 (1987) 86-94.

[42] J.W. Drower, Science, Society, and the Japanese Atomic-Bomb Project During World War Two, Bull. of Concerned Asian Scholars, 10 (April-June 1978) 41-54.

[43] D. Swinbanks, Physicists reveal glimpses of Japan's atomic bomb effort, Nature, 376 (25 July 1995) 284.

[44] Proc. of the 12th EMIS conference, Nucl. Inst. and Methods, B70 (1992) 21, 26, 33, 37-40.

[45] O. Kofoed-Hansen and K.O. Nielsen, Measurements on shortlived radioactive krypton isotopes from fission after isotopic separation, Dan. Mat. Fys. Medd. 26, No. 7 (1951).

[46] H.L. Ravn, Experiments with intense secondary beams of radioactive ions, Phys. Rep. 54, No. 3 (1979) 201-259.

[47] J. Grinevald, A. Gsponer, L. Hanouz, P. Lehmann, La quadrature du CERN (Editions d'en bas, Lausanne, 1984) 186 pp.

[48] Rapports aux Etats membres 1952-1954, CERN 55-1 (1955) p.49.

[49] NA10 Collaboration, L. Anderson et al., A high-resolution spectrometer for the study of high-mass muon pairs produced by intense hadron beams, Nucl Inst. and Methods 223 (1984) 26-39.

[50] P. Astbury et al., Measurement of the differential cross section and spin-correlation parameters P, A and R in the backward peak of pion- p at 5 GeV/c, Nucl. Phys. B99 (1975) 30-52.

[51] In this paragraph we summarize information given by W.E. Burrows and R. Windrem at pages 32-46 of their book Critical mass: the dangerous race for superweapons in a fragmenting world (Simon and Schuster, New York, 1994) 572 pp.

[52] L.M.C. Dutton et al., Small-angle d-p elastic scattering at 1.69 GeV/c, Nucl. Phys. B9 (1969) 594-604.

[53] B. Aebischer et al., Inclusive production of massive muon pairs with intense pion beams, Letter of intent CERN/SPSC 77-20 (1 March 1977).

[54] Obituary, Mario Morpurgo, CERN Courier (September/October 1990) p. 51.

[55] O.B. Nielsen and O. Kofoed-Hansen, A six gap beta-ray spectrometer, Dan. Mat. Fys. Medd. 29, No.6 (1955).

[56] H.O.W. Richardson, Magnetic focusing between inclined plane pole-faces, Proc. Phys. Soc. London, 59 (1947) 791.

[57] O. Kofoed-Hansen, J. Lindhard and O.B. Nielsen, A new type of beta-ray spectrograph, Dan. Mat. Fys. Medd. 25/, No.16 (1950).

[58] Report on the eighth on-site inspection in Iraq under Security Council resolution 687 (1991), 11-18 November 1991, Security Council document S/23283.

[59] J.C. Davis and D.A. Kay, Iraq's secret nuclear weapons program, Physic Today (July 1992) 21-27.

[60] D. Albright and M. Hibbs, Iraq's bomb: blueprints and artifacts, Bull. of the Atom. Scientists (Jan/Feb 1992) 30-40.

[61] Consolidated report on the first two IAEA inspections under Security Council resolution 687 (1991) of Iraqi nuclear capabilities, Security Council document S/22788, 15 July 1991.

[62] Report on the third on-site inspection in Iraq under Security Council resolution 687 (1991), 7-18 July 1991, Security Council document S/22837.

[63] Comments on the Report on the third IAEA on-site inspection in Iraq

under Security Council resolution 687 (1991), 8 August 1991, Security Council Document S/22912.

[64] C.W. Snyder et al., A Magnetic Analyzer for Charged-Particles from Nuclear Reactions, Rev. Sci. Inst., 21 (1950) 852-855.

[65] D. Albright and M. Hibbs, Iraq's nuclear hide-and-seek, Bull. of the Atomic Sci., (September 1991) 14-23.

[66] A. Gsponer, Particle accelerators: the beginning of a discussion, Accepted by the Bulletin of the Atomic Scientists, (May 1982), censured.

[67] D. Shapely, H-bomb issue hits were it hurts, Science, 203 (1979) 1323.

[68] C. Anderson, Classification Catch-22, Nature 356 (1992) 274.

[69] D. Charles, Iraq clings to its nuclear secrets, New Scientist, (27 July 1991) 10.

[70] A. Gsponer and B. Jasani, Particle beam weapons: A need for re-assessment, GIPRI-80-08, submitted to Nature, unpublished (1980) 6 pp.

[71] A. Gsponer, Beam propagation for particle beam weapons, ISRI-82-04, unpublished (1982) 72 pp.

[72] S. Erkman, Bombe atomique: l'Irak est passé par le CERN, Journal de Genève, 22-23 avril 1995, p.1, p.5 .

[73] D. Butler, Laser test facility 'will maintain deterrence' , Nature 375 (4 May 1995) 6.

[74] R. Koenig, Reactor project presses ahead despite protests, Science, 269 (4 August 1995) 627-628.

[75] Clinton neutron promise, Nature 376 (27 July 1995) 282; Neutron source plans face uncertain future, ibid, 285.

[76] J. Weisman, Could defense accelerator be a windfall for science?, Science, 269 (18 August 1995) 914-915.

[77] C. Macilwain, US reduces options on disposal of plutonium, Nature 370 (11 August 1994) 404.

[78] Ann MacLachlan, Rubbia accelerator-generator gets skeptical scientific reception, Nucleonic Weeks (December 9, 1993) 14.

[79] CERN Energy amplifier, CERN Courier, April/May 1995, 7-8.

[80] L.-E. de Geer, The radioactive signature of the hydrogen bomb, Science

and Global Security, 2 (1991) 351-363.

[81] A.B. Lovins, Nuclear weapons and power-reactor plutonium, Nature 283 (1980) 817-822.

[82] M. Cross, Japans's plutonium stockpile, New Scientist (1 February 1992) 34-38. See also S.S. Harrison, Le Japon s'interroge sur ses alliances, Le Monde diplomatique, No 498 (Septembre 1995) 8.

[83] IAEA document INFCIRC209 Rev.1 (November 1990).

[84] A. Schaper, Arms control at the stage of research and development? - The case of inertial confinement fusion, Science & Global Security, 2 (1991) 279-299. See also, E. Arnett (ed), Implementing the Comprehensive Test Ban: New Aspects of Definition, Organization and Verification, SIPRI Research Report No. 8 (Oxford University Press, Oxford, 1994)

[85] A. Gsponer, Science, technique et course aux armements, Dossier du GRIP, No 97-98-99 (Bruxelles, 1986) 13-30. A. Gsponer, L'arme et le gadget, document de travail No 35, Fondation pour le progrès de l'homme (Paris, août 1993) 149 pp.

[86] A. Gsponer and J.-P. Hurni, Antimatter underestimated, Nature 325 (1987) 754; A. Gsponer and J.P. Hurni, Antimatter induced fusion and thermonuclear explosions, Atomkernenergie/Kern-technik, 49 (1987) 198-203.

[87] W. Panofsky, Science, technology and the arms race, Physics Today (June 1981) 32-41.

[88] R.W. Lee, Science on NIF, Energy and Technology Review, Lawrence Livermore Laboratory, (December 1994) 43-54.

[89] J. Nuckolls, Post-cold war nuclear dangers: Proliferation and terrorism, Science 267 (1995) 1112-1114.

[90] G. Taubes, The defense initiative of the 1990s, Science 256 (1995) 1096-1100.

[91] D. Albright and M. Hibbs, Iraq's Quest for the Nuclear Grail: What can we learn?, Arms Control Today, (July/August 1992) 3-11.

[92] D. Albright, A proliferation primer, Bull. of the Atomic Sci. (June 1993) 14-23.

[93] R. Sliver, Ex-safeguards head sees threat continuing from Iraq, North Korea, Nucleonics Weeks (October 21, 1993) 7-8.

[94] M. Hibbs, Second Iraqi defector led IAEA to document trove, Nucleonics

Week (October 3, 1991) 3-5.

[95] D. Albright and M. Hibbs, Iraq and the bomb: were they even close?, Bull. of the Atomic Sci., 47 (March 1991) 16-25. D. Albright and M. Hibbs, Hyping the Iraqi bomb, ibid, 26-28.

[96] J. S. Nye, Jr., New Approaches to Nuclear proliferation policy, Science 256 (1992) 1293-1297.

[97] A. Sanguinetti, Ruptures dans la doctrine francaise de dissusasion, le Monde Diplomatique, No 498 (Septembre 1995) 3.

Appendix

Annex 1 of UN Security Council document S/22872/Rev.1

DEFINITIONS

For the purpose of UN Security Council Resolutions 687 and 707, the following definitions will be adopted:

NUCLEAR MATERIAL

1.1 "Source material"
Uranium containing the mixture of isotopes occurring in nature; uranium depleted in the isotope 235; thorium; any of the foregoing in the form of metal, alloy, chemical compound or concentrate.

1.2 "Special fissionable material"
Plutonium-239; uranium-235; uranium-233; uranium enriched in the isotopes 235 or 233; any material containing one or more of the foregoing.

1.3 "Nuclear-weapon-usable material"
Nuclear material that can be used for the manufacture of nuclear explosive components without transmutation or further enrichment, such as plutonium containing less than 80 % plutonium-238, uranium enriched to 20 % uranium- 235 and uranium-233 or more; any chemical compound or mixture of the foregoing. Plutonium, uranium-233 and uranium enriched to less than 20 % uranium-235 contained in irradiated fuel do not fall into this category.

NUCLEAR ACTIVITIES

2.1-2.9 (inclusive) refer to activities prohibited under both Resolutions 687 and 707.

Any activity such as research and development, design, manufacturing, import of systems, equipment and components, pilot plant and plant construction,

commissioning and operation, or utilization in one or more of the following:

2.1 Production of nuclear weapons

2.2 Production and any use of nuclear-weapon-usable material

2.3 Production of metals and alloys containing plutonium or uranium

2.4 Weaponization
This covers the research, development, manufacturing and testing required to make nuclear explosives from special fissonable material.

2.5 Nuclear fuel fabrication using plutonium, uranium-233, uranium enriched to 20 % or more in uranium-235.

2.6 Import, construction or use of research and power reactors of any kind utilizing uranium enriched to $\geq$ 20 % in uranium-235, uranium-233, plutonium or MOX as a fuel or any reactor designed specifically for plutonium production. This includes critical and subcritical assemblies.

2.7 Reprocessing of irradiated fuel
Including the use of hot cells and the associated equipment

2.8 Enrichment of uranium in the isotope 235 and any preparatory steps in this process, including the preparation of UCl_4 and UF_6.

2.9 Production and separation of the isotopes of plutonium, hydrogen, lithium and boron

2.10-2.18 (inclusive) refer to activities, permitted under resolution 687 but prohibited under 707.

Any activity such as research and development, design, manufacturing, import of systems, equipment and components, pilot plant construction, commissioning and operation, or utilization in one or more of the following:

2.10 Import, construction or use of research and power reactors of any type utilizing natural uranium or uranium enriched to less than 20 % in uranium-235 as fuel. This includes critical and sub-critical assemblies, but excludes reactors specifically designed for plutonium production.

2.11 Prospecting, mining or processing of ores containing uranium and/or thorium

2.12 Preparation of chemical compounds containing uranium enriched to less than 20 % in uranium-235 and thorium, excluding the preparation of UCl_4 and UF_6.

2.13 Nuclear fuel fabrication using natural uranium or uranium enriched to less than 20 % in uranium-235.

2.14 Processing and disposal of radioactive wastes

2.15 Nuclear fusion experimental devices based on magnetic or inertial confinement, including diagnostics

2.16 Production of isotopes both radioactive and stable. The production of the isotopes of plutonium, hydrogen, lithium, boron and uranium is prohibited.

2.17 Import, construction and use of neutron sources, electron accelerators, particle accelerators, heavy ion accelerators

2.18 Research on radiation physics and chemistry and on the physical and chemical properties of isotopes except in area relevant to items 2.19, 2.20 and 2.21

2.19-2.21 (inclusive) refer to activities permitted under resolution 707

2.19 Application of radiation and isotopes in food and agriculture

2.20 Applications of radiation and isotopes in medicine

2.21 Application of radiation and isotopes in industrial processes

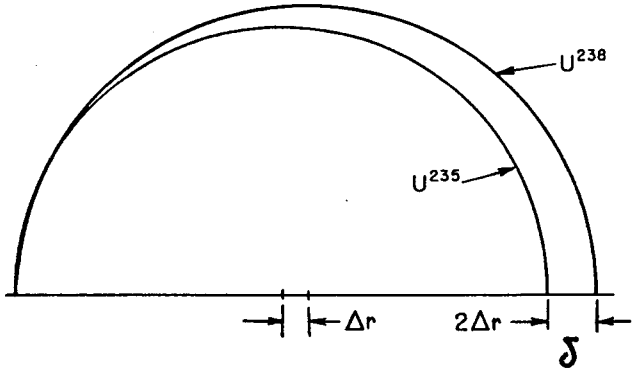

Fig. 1a—Trajectories of U-235 and U-238 ions.

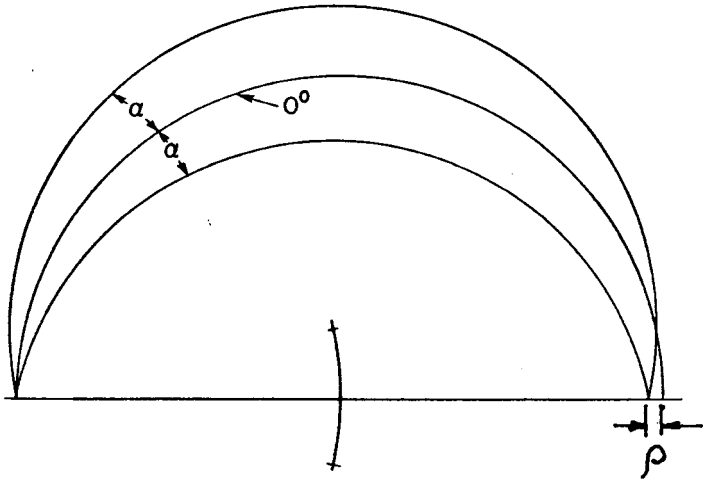

Fig. 1b—Trajectories of ions of the same mass leaving the source at different angles.

Fig. 1—Trajectories of ions in a 180° calutron

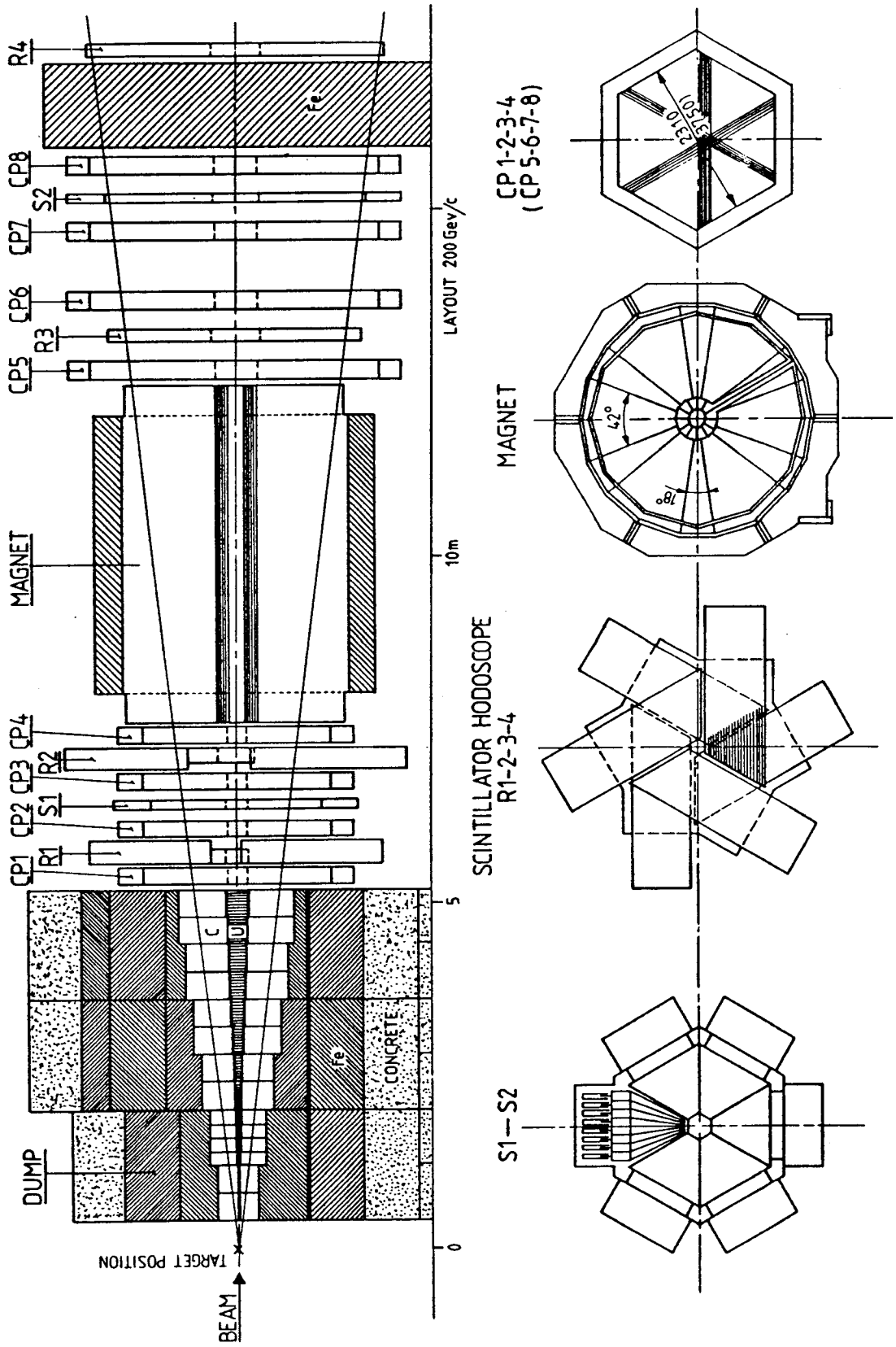

Fig. 2—Spectrometer of experiment NA10. The outer diameter of the magnet is 410cm.

Nuclear Physics B99 (1975) 30–52

MEASUREMENT OF THE DIFFERENTIAL CROSS SECTION AND THE SPIN-CORRELATION PARAMETERS P, A, AND R IN THE BACKWARD PEAK OF $\pi^- p \to K^0 \Lambda$ AT 5 GeV/c †

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We present measurements for the baryon-exchange reaction $\pi^- p \to \Lambda K^0$ at 5 GeV/c over the range $-u < 2\,(\mathrm{GeV}/c)^2$. The differential cross section is obtained from events produced on a liquid hydrogen target. These data are combined with events produced on a butanol polarized target and the parameters P, A, and R are then determined from an analysis of the decay angular distribution of the forward-going Λ. From our data it is possible to determine the magnitudes and the relative phase of the two invariant amplitudes A' and B. The consequences for the ratio B/A' are discussed in detail.

1. Introduction

We present a "complete" measurement in the backward peak of the reaction $\pi^- p \to K^0 \Lambda$ at 5 GeV/c using a butanol polarized target and a liquid hydrogen target.

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Fig. 3a—Front page of reference 49.

Nuclear Instruments and Methods in Physics Research 223 (1984) 26–39
North-Holland, Amsterdam

A HIGH-RESOLUTION SPECTROMETER FOR THE STUDY OF HIGH-MASS MUON PAIRS PRODUCED BY INTENSE HADRON BEAMS

NA10 Collaboration

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Received 7 November 1983

We describe the design, construction and performance of a high-resolution spectrometer used at CERN to study the production of high-mass muon pairs by intense hadron beams. We also discuss the on- and off-line software used with this spectrometer.

1. Introduction

The spectrometer described here was designed to measure, with high statistics and good mass resolution, the production of high-mass muon pairs by pions [1]. As the cross-section for such a process is very low (a few picobarns for masses above 10 GeV/c^2), special attention was devoted to the optimization of parameters governing luminosity and sensitivity, keeping a good mass resolution.

High luminosity is provided by a very intense beam (up to 2×10^9 π^- per burst at 200 GeV/c), a heavy nuclear target (12 cm of tungsten), and a large acceptance spectrometer which measures and identifies the muons (fig. 1). Correspondingly, the detectors were designed to stand efficiently high rates [10 MHz for the counters and 100 kHz for each wire of the multiwire proportional chambers (MWPCs)], and to allow for a good mass resolution (20%) at the trigger level.

The trigger is formed with signals from two sets of two hodoscopes, one set located upstream (R1 and R2) and the other downstream (R3 and R4) of a spectrometer magnet. Their geometry and granularity were chosen to allow fast and selective triggering on muons pointing at the target and having transverse momenta in a specified range.

The measurement of the trajectories of the muons before and after deflection by the azimuthal magnetic field is performed with two corresponding sets of four MWPCs. The final mass resolution (3–4%) is determined by the accuracy with which angles and momenta are measured, and is limited by multiple scattering and energy loss straggling in the hadron absorber and by the uncertainty of vertex localization.

2. Beam line and monitoring

2.1. Hadron beam

The spectrometer is located in the CERN North Area High-Intensity Facility [2] at the end of a high-intensity hadron beam. This beam line can transport primary protons and negative secondaries of up to 450

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[e] Now at INFN, Sezione di Roma, Italy.
[f] Now at GIPRI, Geneva, Switzerland.
[g] Now at CEA, Valduc, France.
[h] Now at SLAC, California, USA.
[i] Now at Centro di Fisica da Materia Condensada, Lisbon, Portugal.
[j] Present address: Reynolds Farm, Cassington, Oxford, England.

Fig. 3b—Front page of reference 50.

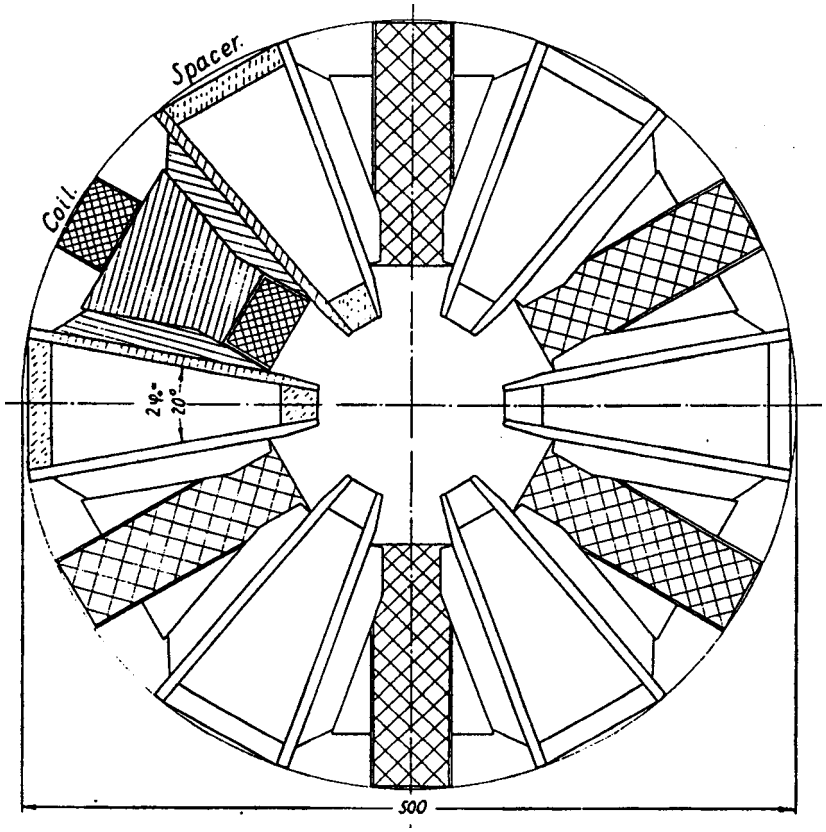

Fig. 4—Section through the Risø spectrometer. The outer diameter of the magnet is 50cm.

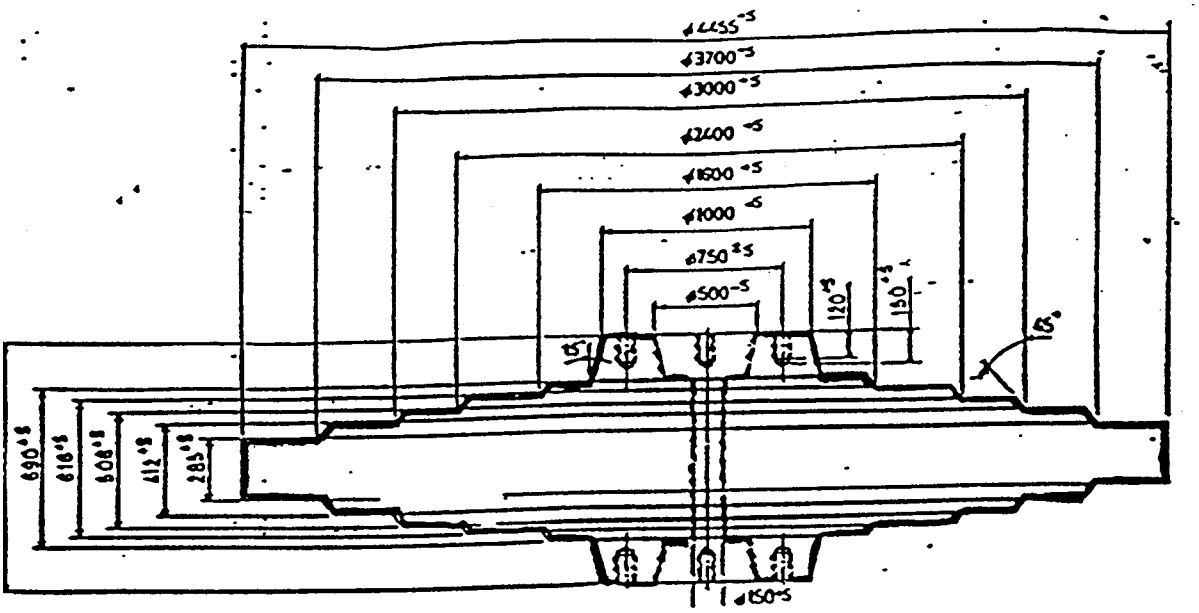

Fig. 5a—Pre-machined iron core for 120cm beam radius magnets.

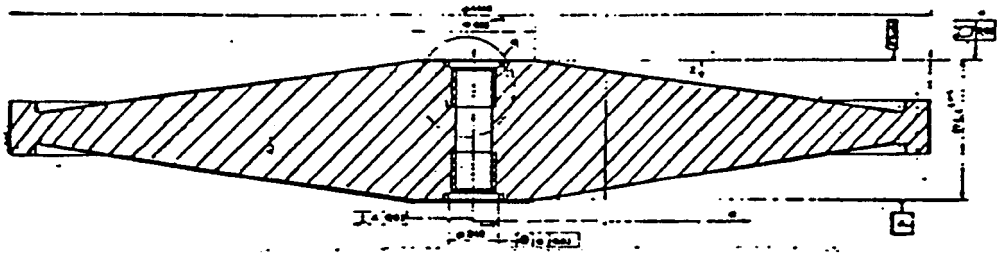

Fig. 5b—Final dimensions of 120cm beam radius magnet cores.

Fig. 5—Cross section of Iraq’s alpha calutron magnet cores.

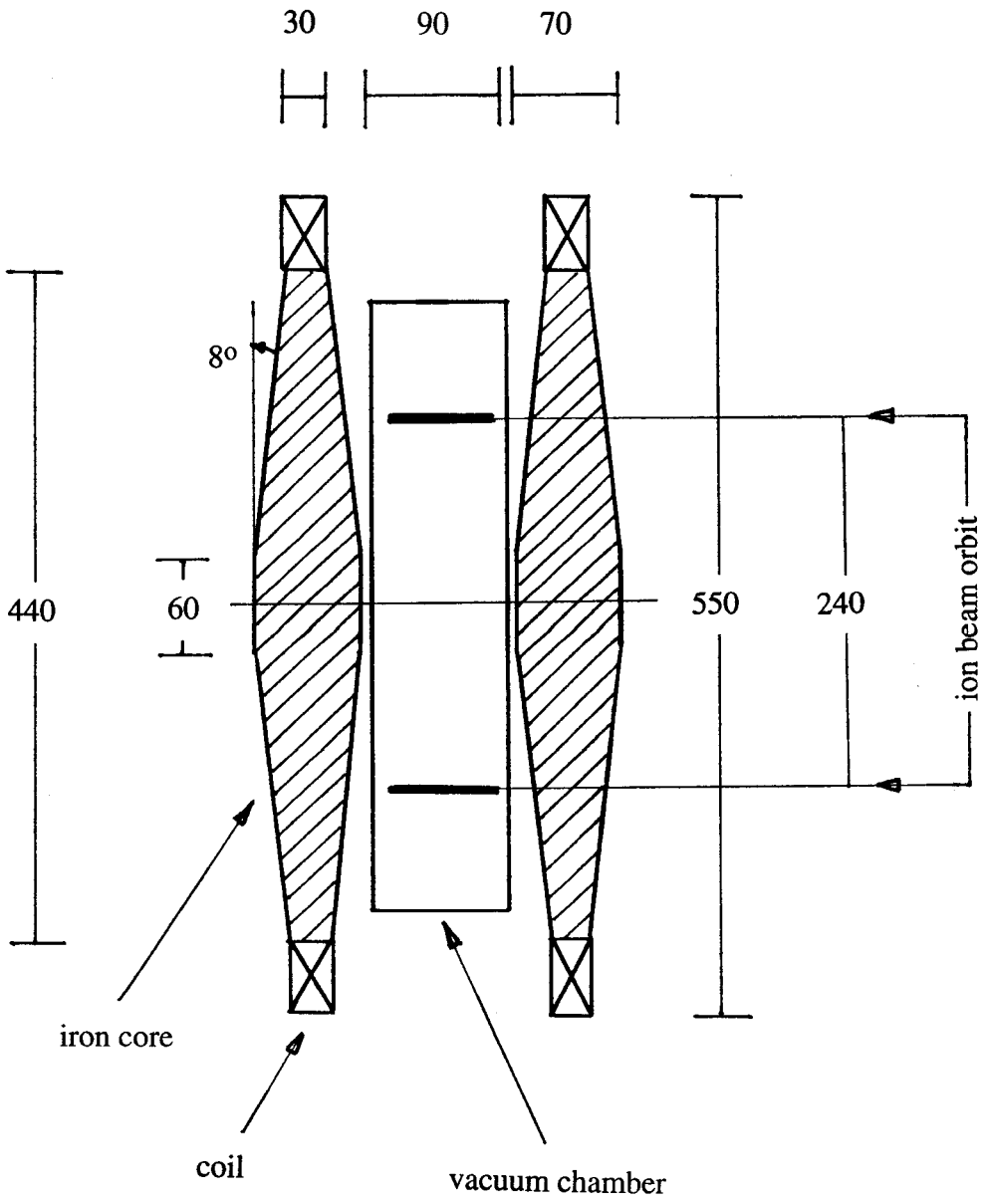

Fig. 6—Schematic of Iraq's alpha calutron track.
Only two adjacent magnets and one separation chamber is shown.

Fig. 7a—Alpha calutron chamber on its side.

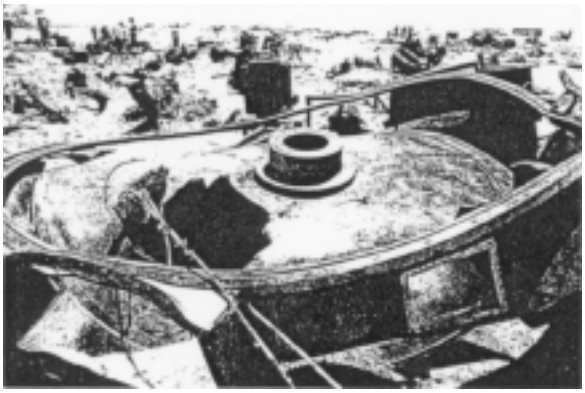

Fig. 7b—Crushed beta calutron chamber.

Fig. 7—Photographs of Iraqi alpha and beta calutron chambers.