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ACCELERATORS : A WIDE FIELD FOR SCIENCE AND TECHNOLOGY TRANSFER TOWARDS DEVELOPING COUNTRIES.

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Abstract :

Accelerators of low and intermediate energy, particularly electrostatic generators and cyclotrons, are suitable tools for basic and applied research that developing countries can acquire. The current status and the development in progress concerning such equipment as well as the field of research are outlined.

1. INTRODUCTION

In advanced countries, nuclear facilities are built around either a nuclear reactor or an accelerator. Although a nuclear reactor is, usually, directed towards power technology investigations whereas an accelerator is, in principle, devoted to basic research, both of them are, in practice, used to applied and basic research.

I will restrict my talk to accelerators in order to show the wide range they display in size, technical complexity, cost and capabilities and, therefore, the great number of possible choices they offer.

Retaining the low and intermediate energy accelerators as the most convenient ones for a starting program in a developing country, I will outline the basic and applied research currently performed by these accelerators and I will give some typical examples. The recent advent of the superconducting cyclotron justifies the emphasis I place on it in order to take into account the lack of commercial information consequent on its novelty.

I would like to emphasize that the achieved sophisticated accelerators must be understood as the result of a steady increase of progress in numerous various fields as radiofrequency systems, accelerating cavities, ion sources, magnets, cryogeny, vacuum, data processing, ... On the other hand, performing nuclear experiments requires a constant dealing with the special techniques of detection, magnetic spectrometry, pulse electronics, numerical treatment and a continuous renewing of knowledge in theory. So, working with an accelerator and a detection equipment leads to a continuous activity in a variety of modern techniques and in physics principles; such an activity is desirable for the staff of a University, in a developing country, in order to reach in nuclear field a scientific level comparable to that in advanced countries. In addition to basic nuclear research, a harmonious use of the equipment can cover laboratory teaching and applications into, either, other basic domains such as analytical chemistry, solid state physics, archaeology, or, applied fields as activation analysis, medical diagnosis, agriculture...

2. ACCELERATOR TYPES

The history of the accelerators building is displayed in the famous Livingstone Chart[1] presented here in figure 1. Each point represents an accelerator built with the highest energy for its type and at its time. Each line joins accelerators of a given type and characterized by a specific technology. At the beginning of each new technology the chart shows a rapid increase in the achievable energy and then a levelling off as that technology appears to be fully exploited. The rectifier generator and the electrostatic generator are the oldest and the widely used low energy accelerators : the ions acceleration is accomplished inside an accelerating tube between the extremities of which is applied a high voltage obtained, in rectifier generator, by rectification of an alternative voltage and, in electrostatic generator, by transporting electric charges to a conducting terminal. We will give, in a next section, a list of such commercially available accelerators and a

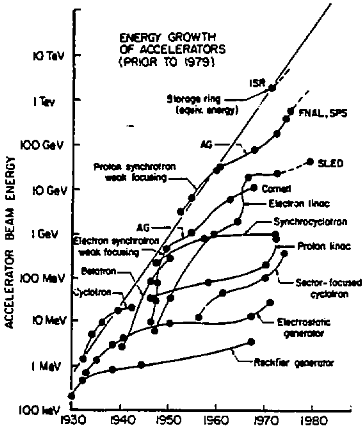

Figure 1 : Livingstone Chart, displaying the history of the accelerators building.

comment on the largest operating models, i.e. tandems (a tandem is a special Van de Graaff accelerator where the high voltage of the terminal is used twice for two stages of acceleration of the same particle).

We exclude, in this talk, the high energy ($\gtrsim$ 1 GeV) accelerators and the electron accelerators that are too specialized in particle physics. We exclude, also, proton linacs for their electromagnetic complexcity.

Focusing our attention on circular accelerator types where accelerating is accomplished on a circular path of the particles by a relatively low voltage, we exclude the old types, e.g. the conventional cyclotron and the synchrocyclotron and we retain the sector-focused cyclotron called, also, the isochronous cyclotron or the AVF (azimutal variable field) cyclotron, which is the modern accelerator by its relative simplicity, small cost and high performance in the energy range from 10 MeV/nucleon to a few hundreds MeV/nucleon. I have proposed, in 1974, an isochronous cyclotron of 40 MeV proton to neighbouring arab countries[2]. However, recently, the syperconducting magnets technology has permitted the advent of the superconducting isochronous cyclotron, which, compared to a room temperature cyclotron of the same capabilities, has a smaller size, 2 or 3 times lower cost and consumes several times less in electric power. Presently,[3] there are well advanced projects as well as various proposals for superconducting cyclotrons, around the world. In fact, the desigred superconducting cyclotrons projects promise to the nuclear physiscist the high quality ions beam he desires, i.e. :

- an energy range from ten to several hundreds of MeV/nucleon
- a variability in energy attaining a ratio $E_{max}/E_{min} \approx 5$ to 10
- polarized beams
- an energy resolution of $\approx 10^{-4}$
- an emittance $<\pi$ mm-mrad
- a macroduty cycle $\gtrsim$ 100 %

3. THE ADVENT OF THE SUPERCONDUCTING CYCLOTRON

The use of superconductivity provides magnetic fields in the range of 25 to 50 kgauss which are much higher than those of at most 18 kgauss encountered in ordinary cyclotrons. At these values the steel is completely saturated. It is the resulting increase of the midplane induction B which permits the decrease of the radius ρ in the product ρB necessary to bend a particle. Superconducting cyclotrons are well suited to the acceleration of heavy ions which require large ρB products.

A superconducting cyclotron consists, as the AVF cyclotron, of iron sectors for the field modulation necessary to the axial focusing and has an average magnetic field increasing with radius in order to insure the isochronism. Two relationships define the operating range of a superconducting cyclotron[4] :

$$\frac{T}{A} \leq K_{Foc.} \frac{Z}{A} \quad \text{and} \quad \frac{T}{A} \leq k \left(\frac{Z}{A}\right)^2$$

where T is the kinetic energy, A is the atomic number and Z the charge number of the ions beam; the constant K is proportional to $\bar{B}^2\rho^2$, $\bar{B}$ and ρ being the field and the radius at extraction respectively. The first relationship is deduced from the axial focusing requirement and the second is the usual bending condition. The constant K_{Foc} does not exceed approximately 1/3 of K value. Therefore, in determining the maximum energy for a given ion, the first relationship applies for $\frac{Z}{A}$ values higher than approximately 0.3, whereas the second one applies for lower Z/A values.

The occurrence of axial or radial resonance, in cyclotrons, sets limits to their performance. For a three sector cyclotron (N = 3), the absolute maximum energy which could be reached is about 220-240 MeV/nucleon, due to the radial (axial) resonance $\frac{N}{2}$. For a four sector geometry the maximum energy would be 380-400 MeV/Nucleon. The other resonances resulting from the coupling between axial and radial motion limit the dynamic range of the cyclotron.

The K = 500 superconducting cyclotron, also called phase I, of the Michigan State University superconducting program will operate, first throughout the world, by the end of this year. The operation of the K = 800 cyclotron of phase II which will be coupled with the first cyclotron is scheduled for 1984. There are three other cyclotrons which are in construction, one of K = 520 at Chalk River (Canada), an other of K = 800 at the University of Milan and the third of K = 500 at Texas A and M University; each of them will be coupled with a tandem Van de Graaff or another cyclotron ; their operation is scheduled for 1984-86. On the other hand, there are several projects in progress around the world.

At Orsay, there is a group performing a design study for a K = 600 three-sector cyclotron with either radial injection from a 15 MV tandem or axial injection from an electron beam ion source (EBIS). The group, equivalent to five full time engineers and four full time physicists is planning to achieve the definition of the cyclotron for may 1982. The capabilities[5] of the cyclotron are summarized in table 1.

	accelerated ions	E_{min} ——— E_{max}	$\frac{\Delta E}{E}$	beam intensity in particle/s
light ions	p and $\vec{p}$	40 ——— 200 MeV	5.10^{-4}	10^{12} - 10^{13}
	d, He and $\vec{d}$	20 ——— 100 MeV/u	5.10^{-4}	10^{12} - 10^{13}
heavy ions	A ≤ 40	4 ——— 100 MeV/u	5.10^{-4}	5.10^{11} - 10^{10}
	A ≈ 80	4 ——— 80 MeV/u	10^{-3}	5.10^{10} - 10^{9}
	A ≈ 200	4 ——— 50 MeV/u	10^{-3}	5.10^{10} - 10^{9}

Table 1 : Summary of the capabilities of the Cyclotron in project at Orsay.

Beside its performance for light particles, this cyclotron has good capabilities for heavy ions. It is thought that this cyclotron with the tandem used as injector will be in 1988-89 the only machine replacing the three accelerators operating now at the Institut de Physique Nucléaire of Orsay, e.g. the synchrocyclotron of 200 MeV proton, the ALICE system (a LINAC coupled to a K = 70 cyclotron) and the 13 MV tandem.

4. THE CURRENT STATUS IN ELECTROSTATIC ACCELERATORS

A great number of electrostatic generators, Van de Graaff and small tandem accelerators are, at present, operating throughout the world, most of them installed since more than ten and even fifteen years. Delivering light ions beams (p,d and He) and recently heavy ions beams up to a few MeV/nucleon, they were, in the past, powerful tools in beginning nuclear physics research but they are at the moment, after the growth of the energetic accelerators, devoted to applied research. Their specific role in applied research will be illustrated later by typical examples. However, one can say their present use does not cease to justify their continuous construction and commercialization. We list in table 2 the high voltage and beam intensity values for the HVEC available models[6].

	Van de Graaff						Tandems
High Voltage	400 kV	750 kV	2.5 MV	3 MV	4 MV	5.5 MV	2x3 - 2x13 MV
Beam intensity	100 µA	100 µ	150 µA	400 µA	400 µA	50 µA	a few µA

Table 2 : Characteristics of HVEC available models.

Let us mention the special category of the fast neutron generators, in particular that producing 14 MeV neutrons by the reaction $T(d,n)\alpha$. The deuteron beam is, generally, accelerated by a rectifier generator delivering a high voltage of about 200 kV. Sealed tubes and long-lived sources of low flux (10^8 neutrons/s) or high flux (10^{12} n/s) are commercially available[7]. The accelerators of this category are specialized, particurly, in bulk determination of light elements for industrial purposes.

In the course of the last 15 years, large tandems (H.V. ≃ 13 MV) were built offering with regard to small van de Graff two powerful advantages, namely, a production of light ions beams (p,d, ^{3}He and α) with higher energy and the acceleration of heavy ions up to A ≳ 60. Ten such tandems of 13 MV (model MP of HVEC) have been, already, in operation for many years in American and European laboratories[8]. Recently, eight similar or even somewhat larger models (HV = 16-25 MV) of giant size came either into construction or into operation throughout the world. Let us point out, here, that large tandems have undergone many developments and improvements during their exploitation in such a way that the only remaining unchanged part are usually the basic column structure and the tank : the original charging belt was systematically replaced by Pelletron chains or Laddertron, new type ions sources were installed, insulating gaz mixture was improved, pumping system was changed... the general trend in the development being towards an upgrading in energy and a coupling with a new superconducting cyclotron.

5. BASIC RESEARCH FEATURES WITH ACCELERATORS

The basic research undertaken, at present, with either Van de Graaffs or cyclotrons, involves, in fact, problems of the same nature in nuclear spectroscopy and nuclear reactions mechanisms. A general feature related to the magnitude of the energy available in these accelerators may be drawn : higher energy beams overcome more easily Coulomb barrier when they bombard a target nucleus, thus, inducing more reaction mechanisms and larger cross-sections and, therefore, offering more means of exploration.

As a consequence of this feature, tandems and cyclotrons have, presently, the advantage over small van de Graaffs in nuclear research.

On the other hand, many uses in other fields than nuclear physics and in practical applications have, recently, turned out to be appropriate to low energy accelerators or of a too high cost with higher energy ones; that has made small accelerators to specialize in applied research and to serve only on occasion or on part-time for some basic experiments justified, generally, by an elaborate theoretical contribution.

The numerous phenomena observed in nuclear physics, early with small Van de Graaff and recently with tandems and cyclotrons, find an overall explanation within the shell model and the unified model of Bohr and Mottelson and by involving the concepts of compound nucleus and direct reaction mechanisms. However, exact solution for problems implying nuclear forces interaction is, still, far from being reached, due both to the complexity of the nuclear forces themselves or simply to mathematical difficulties. So, further efforts should be carried on for exploring better and vaster, using the wealth of existing means offered by accelerators, e.g. a great number of projectiles, a wide range of energy and a variety of nuclear reactions. To the traditional nuclear reactions as elastic, inelastic scattering or nucleons transfer and charge exchange reactions, one has, now, to join the recently known reactions induced by heavy ions beams, where considerable transfer of mass, fusion or explosion of the projectile and of the target, occur.

The regular international conferences on nuclear physics report on studies currently undertaken at different laboratories, see for example reference 9.

As a typical result in traditional nuclear physics performed with light ions, we present in figure 2 a spectrum of the excitation energy in ^{89}Zr obtained[10] by the reaction $^{90}Zr(^3He,\alpha)^{89}Zr$. The ^3He beam of 39 MeV is delivered by the MP tandem of Orsay and the emitted α-particles are

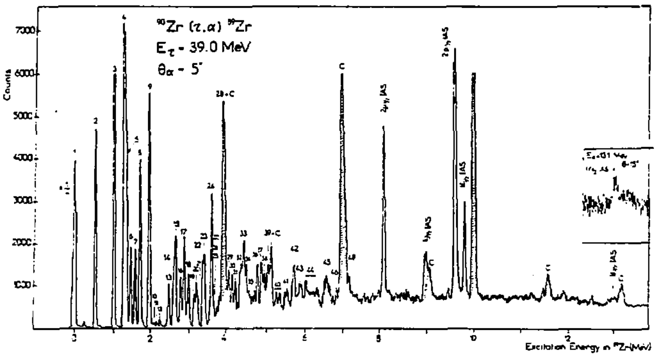

Figure 2 : The spectrum of excitation energy in ^{89}Zr, measured in the reaction $^{90}Zr(^3He,\alpha)^{89}Zr$ at 39 MeV and at $\theta_\alpha = 5°$.

detected by a Si detector placed in the focal plan of a split-pole spectrometer, giving together an energy resolution of 30 keV. In the figure, the numbers at the top of the peaks refer to nuclear levels in ^{89}Zr, while the letter C refers to peaks originating from the carbon as a contaminant in the target. The well-resolved peaks in the energy range 0 - 3.5 MeV correspond to a pick-up of a neutron from the outer filled subshells of the shell model in ^{90}Zr, i.e. $1g_{9/2}$, $2p_{1/2}$, $2p_{3/2}$, $1f_{5/2}$. The group of levels observed around 4.5 MeV corresponds to the fragmentated strength of the $1f_{7/2}$ subshell. The sharp peaks observed above 8 MeV in excitation energy are the isobaric analog states in ^{89}Zr. The growing background reflects, here, the growing density of the final states of the transfer reaction.

As a typical result in nuclear physics performed with heavy ions we present in figure 3 isotopic distributions obtained[11] by the reaction $^{40}Ar + ^{238}U$. The ^{40}Ar beam was accelerated to 340 MeV by the Orsay-ALICE facility. The emitted nuclei are detected by a time of flight system using channel plates as time detectors and then by a three member Si counters telescope; an unambiguous

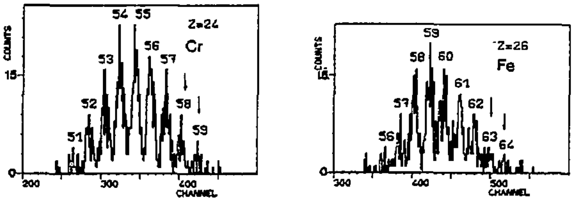

Figure 3 : Isotopic distributions for species of Z = 24 and 26 emitted in the reactions $^{40}Ar + ^{238}U$ at 340 MeV.

identification in charge number Z and atomic number A is deduced. In the figure, arrows mark the newly synthetized isotopes by this experiment. These synthetized isotopes rich in neutrons can be considered as projectile like nuclei emitted after equilibration of their $\frac{N}{Z}$ degree of freedom with the large one of the U.

6. TYPICAL APPLICATIONS OF ACCELERATORS

We have chosen a few applications among the numerous existing ones that we believe to be interesting for developing countries.

6.1 - Role of the cyclotron in tumour radiography

Recent work, reported in reference 12, suggests that charged particles delivered by a cyclotron have a great potential for detection of small tumours with lower doses of radiation than in X - radiography and for detection of minute diffusely distributed lesions. An arrangement to observe the lesions and tumour in the human brain is used at Harvard cyclotron. Such arrangement with scanning technique using 200 MeV proton has been developed at Argonne National Laboratory, then at Triumf Laboratory (Vancouver) and at Fermi National Accelerator Laboratory (Chicago).

6.2 - Analysis by nuclear reactions

Analysis is a versatile means in many field, especially when it implies non-destructivity and sensitivity to trace elements, as it is the case in the methods described in this paper. Analysis by nuclear reactions resembles quite closely the way in which nuclear physics research is accomplished. When one bombards a sample with a projectile a nuclear reaction occurs and there is simultaneous or subsequent emission of radiation which are characteristic of the excited nuclei produced; the analysis of the emitted radiations gives the composition of the sample. In order to overcome Coulomb barrier, the majority of reported experiments has been performed with cyclotrons and using light projectiles. The cost may be lowered if a large number of samples is routinely analysed and in particular if multielement analysis is carried out in a single irradiation. Reference 13 describes the method and gives an extensive bibliography. Two examples taken from that reference are :

- inelastic proton scattering on ^{19}F, ^{23}Na and ^{27}Al have been used to analyse fluorine, sodium and aluminium in black volcanic glass obsidian; the irradiation was performed with a 0.6 μA beam of 2.2 MeV protons; a Ge detector was used. The characteristic prompt radiations detected were : 110 and 197 keV γ-rays for ^{19}F, 439 keV γ-rays for ^{23}Na, and, 842 and 1015 keV γ-rays for ^{27}Al.

- the $^{37}Cl(d,p)^{38}Cl$ reaction has been used to detect trace amounts of chlorine on aluminum. The deuteron beam had an energy of 5 MeV and the resulting γ-ray activity was measured in a well-type NaI(Tl) detector.

6.3 - Particle Induced X-Ray Emission

An international conference has, recently, reported on PIXE analysis[14]. In many laboratories its development has already resulted in highly automated systems. This method is now widely used in ambiant aerosol studies and it begins also to be a useful tool in medicine, biology, forensic science, mineralogy and mechanical engineering.

The principle of the method is to create vacancies in atomic shells of a sample when bombarding it with charged particles and to detect the characteristic X-rays emitted when vacancies fill from outer shells. The method requires the particle beam reaches the element under study and the secondary X-radiation can exit from the target for subsequent detections; so, this method face the necessity of thin target, a fact which specializes it for subjects where little material is available, as aerosol analysis.

Reference 15 describes the method and illustrates it by the arrangement of Crocker Nuclear Laboratory (Univ. of California) designed for analysis of atmospheric aerosols. An 18 MeV α-beam was chosen from the 76" isochronous cyclotron. The detector was a 10 mm^2 Si(Li) detector, 3 mm thick, cooled to liquid nitrogen temperature. The detection system used K X-rays from elements Na to I (1.04 keV $\leq E_x \leq$ 28.5 keV), while L X-rays were used for Cs and heavier elements. The analysis of the very light elements (H → F) was performed using α elastic scattering. The reference goes further to the details of data acquisition and reduction, target preparation, matrix effects and finally to the estimation of analytical costs. It appears from the reference that the ability to have reasonable sensitivity for all elements (Na → U) is practically unique to PIXE.

There is another technique, the X-ray fluorescence (XRF), which uses the same detection system than in PIXE but radioactive sources or X-rays tubes instead of the irradiating beam. The XRF technique has, also, a high performance in analysis[15]. Reference 16 compares the two techniques As far as equipment size is involved the XRF technique needs a much simpler irradiating facility, e.g. radioactive sources in the range of 10 Ci of ^{125}I, ^{109}Cd, ^{241}Am, ... or a conventional 100 kV X-ray tube provided with different fluorescer materials.

6.4 - Dating by radiocarbon

Much of the early work on archaeological materials had as its objective the identification of materials. An important turning point was the finding that the concentration of Carbon-14 in living materials could be used as a clock for the period of interest to archaeologists. The principle is the following : the constant interaction of secondary cosmic rays with atmospheric nitrogen produce ^{14}C (half-life of 5 500 yrs), yielding a constant ratio of ^{14}C to ^{12}C in atmospheric CO^2. When living organism dies, its assimilation of atmospheric CO^2 stops and the ratio of ^{14}C to its total carbon weight starts decreasing by ^{14}C decay. Thus, the analysis of the ratio of the ^{14}C to the total carbon amount in archaeological material gives the date of its death. Many laboratories exist around the world which have developed low counting detection arrangement for the detection of the β radiation emitted by ^{14}C and complementary chemical technique required to obtain the ratio of ^{14}C to total carbon. An extensive literature exists about the applications of radiocarbon dating[17]; let us mention, here, archaeology, geology, hydrology, ...

New developments in accelerator technology promise the analysis of ^{14}C, ^{13}C and ^{12}C in either solid carbonaceous or gaseous CO^2 samples of 1 to 2 mg, within a half-hour of counting time and with a precision of ± 1 %. Comparing that to the conventional technique, cited above, which requires 1000 mg samples and a counting time of 10 hours, one realizes that we face a revolutionary technique in radiocarbon analysis. The new technique[18] consists of ionising the sample inside an ion source, accelerating the ions in a tandem accelerator, filtering by electrostatic and magnetic deflectors and counting. At this moment, several tandems are ordered, throughout the world, by laboratories specialized in radiocarbon analysis.

It is worth noting, here, that the recent use of accelerators as ultra sensitive mass spectrometer is not specific to radiocarbon but it is being applied to other elements, e.g. the ^{36}Cl (half-life 305 000 years); the measurement of the ratio of ^{36}Cl to total chlorine in natural samples is used for the dating of very old ground waters[19].

7. CONCLUSION

Having restricted our talk to beam energies ranging from a fraction of MeV per nucleon to a few hundreds MeV per nucleon, this lead us to deal with electrostatic accelerators and cyclotrons. A wide choice in opportunities has been shown, such that the higher is the energy of the accelerator, the larger is its capability in nuclear research. Emphasis has been placed on the ever possible applications even with the smallest accelerators. Current applications with small accelerators being today indispensables in nuclear teaching laboratories, in medicine, ... applications with larger accelerators could be revolutionary for other disciplines, e.g. the use of a tandem as an ultra sensitive mass spectrometer for radiocarbon and other isotopes.

In my talk, I did not mention organization problems inherent to the start and growth of research groups, that could, often, be the more determinant inhibiting reason. I believe that human and organization type problems could be solved in developing countries if the research groups are given, there, a special status very analogous to that of research groups in advanced countries with which a necessary connection must be established.

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