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PRESENT AND FUTURE ROLE OF CYCLOTRONS IN NUCLEAR PHYSICS AND THEIR APPLICATIONS

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Abstract : At the dawn of the next millennium the perspectives of Nuclear Physics have been discussed in details in recent review reports by scientific advisory committees both in Europe and in the US. The emerging field of Radioactive Ion Beams calls from strong development of high power accelerators as drivers or for low-energy (few to 30 Mev /n) machines. The present and future role of cyclotrons in this area is presented. Cyclotrons are intensively used in the applied sector where the main emphasis are on the radioisotope production and hadron therapy. The increasing demand on the world scale for hospital-based facilities for nuclear medecine and therapy are discussed .

I. Introduction

« Moving frontiers in Nuclear Physics »

To present and discuss the perspectives of Nuclear Physics, I would like to use as a more general framework, our present understanding of our universe as illustrated in fig .1.

Only instants (10^{-34}s) after the Big Bang our universe consisted of hot plasma made of free quarks and gluons.

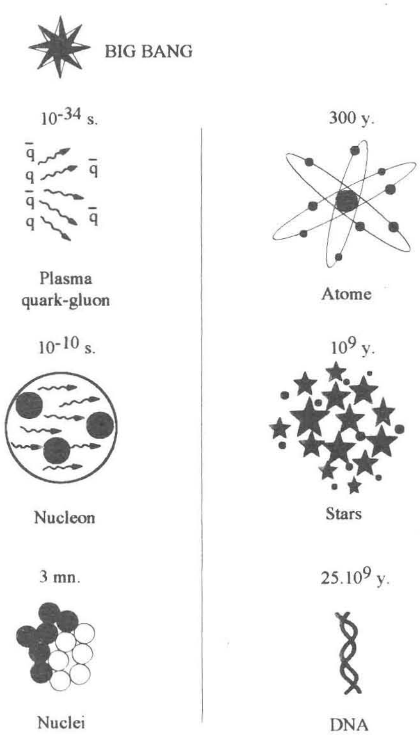

Fig.1 : From the Big Bang to the appearance of life : the different Phases of the evolution of our universe

Nuclear physicists are able to reproduce in the laboratory through ultra-relativistic heavy ion collisions (100 GeV/n to 6000 GeV/n Pb beams) the physical conditions (temperature, density) existing during these early instants of our universe. This quest of the signals indicating that a phase transition from a hot and dense hadron gas into a deconfined plasma of quarks and gluons is one of the major challenge of the field gathering hundred of physicists around the future collider experiments at RHIC (USA) and LHC (CERN).

10^{-10} s after the Big Bang quarks and gluons combined themselves into more complex systems called not so long ago “elementary particles” protons, neutrons and mesons. Although we know that QCD is the proper theory for strongly interacting particles understanding the dynamics of confinement and the formation of hadrons in general is a major challenge of Nuclear Physics to day. The best probe to study this problem and more generally interactions at short distances is electron and muon scattering. One needs high energy, high luminosity continuous electron beams to study the hadron structure and dynamics.

A few minutes later nuclei light first (H, He Li....) and heavy later (from Fe to U) elements have been formed. This is known as the Nucleosynthesis which produced the cold ashes of the primordial explosion : the few hundred elements that are sufficiently stable to form our universe. But during the formation of our universe, many thousands of unstable nuclei were created. Their properties are essentially unknown, and in the near future, a new generation of experimental facilities producing high intensity Radioactive Ion Beams (RIB) will be available to explore this “Terra Incognita”. The exploration of this ephemeral world that exists during the birth and death of stars is one the main avenue of the field with strong overlap with our colleagues from Astrophysics and Cosmology.

II. Cyclotrons : present role and proposals

A close examination of the proceedings of this conference held in 1981 at Caen and in 1995 at Capetown show that the number of cyclotrons in operation for basic nuclear physics has decreased from 53 to 47 during the last 15 years. On the contrary, for the same period a strong development of cyclotrons based facilities for radioisotope production, nuclear medecine and diagnosis as well as other industrial applications have occurred. The statistics indiquate that a total of 42 machines in 1981 to be compared to about 150 units to-day, mostly in Europe, USA and Japan.

The frontiers of the field have strongly evolved leading to closure of many low-energy nuclear physics facilities or their transfer to other fields of basic and/or applied research.

In the meantime, a few new projects have been realised and proposals to build new cyclotrons for basic nuclear physics research are under consideration. These recent developments have rather clear motivations :

i) The cyclotron based facilities which have been realised during the last 10 years correspond :

- to an upgrade of an existing facility (AGOR a K600 superconducting cyclotron operates since 1996 at Groningen in place of the old K160 machine, K800 superconducting cyclotron at the LNS Catane boosting the energy of the 16MV tandem accelerator, K400 ring cyclotron at Osaka).
- to the creation of new centres like at Jyvaskyla (JYFL ,K130) or at Warsaw (HIL , K160).

The facilities mentioned above have all a national character and play an important role at the regional level.

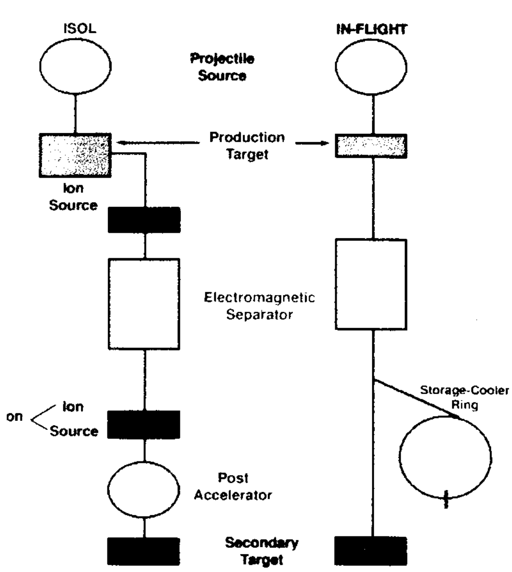

Fig.2 : The two complementary ways of producing Radioactive Ion Beams.

ii) The ongoing developments and the new proposals are oriented towards either the production or the acceleration of RIB.

The two complementary ways of producing RIB are presented in fig.2.

The so-called "**ISOL**" method is characterised by an intense primary beam (protons, fast or slow neutrons, heavy ions) hitting a thick target. The exotic nuclei produced by the reaction will diffuse from the target and are ionized on-line before being sent to electromagnetic separator for isotope selection. The selected species could be further accelerated by injection into a booster .

The "**IN-FLIGHT**" method takes advantage of the high incident velocity of high energy (50 to 1000 MeV/n) heavy ion beams hitting a thin target and producing through the fragmentation process strongly forward focused RIB with roughly the same velocity than the incident beam. An electromagnetic velocity filter can bring the selected exotic nuclei either on a secondary target to induce nuclear reactions or can be sent to a cooler storage ring for further acceleration, deceleration or reaction with internal targets.

In both cases, in order to achieve the highest possible rate of production of RIB one key parameter is the intensity of the primary beam given by the driver accelerator. Various projects of first generation RIB facilities are under construction around the world.

For the ISOL-type, the SPIRAL project at GANIL, the EXCYT project at LNS Catane, Louvain-la-Neuve and ISAAC at TRIUMF will use cyclotrons as drivers. The foreseen beam powers on target will range from 6 to 10KW at Louvain, Ganil and Triumf. At Ganil and at Louvain-la-Neuve, the RIB will be accelerated using cyclotrons as boosters with final energies up to 25 MeV/n and 1 Mev/n respectively. At LNS Catane the booster is the existing 16 MV Tandem and at TRIUMF a combination of RFQ followed by a LINAC is proposed to boost the final energy up to 1-2 MeV/n. Only the REX-ISOLDE project at CERN will use the 1 GeV proton beam from the PS to produce RIB and a LINAC to reach a final energy of 2 MeV/n.

To produce very intense secondary RIB, working groups both in Europe, USA and Japan, are looking into the so-called "second generation ISOL" scheme where one hopes to reach beam power of 1 MW, a factor 100 higher than the one planned to day for the RIB facilities under construction.

For the "IN- FLIGHT" method an intensity upgrade is taking place at GSI in order to reach by the year 2000 the incoherent space charge limit (10^{10} ions/pulse for U) in the SIS synchrotron. The two major fragmentation facilities already operating in the US (MSU-NSCL) and in Japan (RIKEN) have major planned upgrade of their primary beams energy and intensity. At NSCL, the improved acceleration chain will consist of a ECR-ion – source injected in the K500 cyclotron followed by radial stripping injection into the K1200 for final acceleration up to 100-200 MeV/n with an output power of 4 KW. At RIKEN a cascade of a K930 ring cyclotron with 4 sectors and a K2500 superconducting ring cyclotron with 6 sectors will be constructed to boost the energy of the existing K540 cyclotron up to 400 MeV/n for light ions and to 100 MeV/n for very heavy ions.

To be complete, it is worth mentioning the fragmentation facilities SISSI and ACCULINNA, respectively in operation at GANIL and DUBNA which produce light ion radioactive beams in the energy range 30-70 MeV/n.

This short overview of the present and future use of cyclotrons in nuclear physics research clearly shows that cyclotrons will continue to play a key role in the domain of Nuclear Structure Far-off stability, the emphasis being high power driver accelerators .

III. Cyclotrons and applied issues.

The strong R&D programmes carried out around the world to reach high power beams output, the increasing demand of low-energy accelerators for radioisotope production linked to their use in radiobiology and medecine, the hadrontherapy (hadron beams used to kill cancer tumour) and its associated instrumentation, seems to be the main lines of future development for cyclotrons in the applied sector.

First, I would like to stress that " high intensity" is a crucial issue in many fields of science .

I have already discussed the future projects, in particular in North-America, in Europe and in Japan, associated with the **second generation ISOL-RIB** facilities aiming at beam power on target of the order 100KW.

These accelerator performances are not so different from those that neutron community is aiming at for the next generation of **Neutron Spallation Sources.** The European Spallation Source project (ESS) calls for a 1GeV, 5% duty cycle, average beam current of 4mA, proton driver.

For **the inertial fusion** projects, like the IFMF proposal in the USA, a 40 MeV, CW, deuteron beam with an intensity of 100 mA is foreseen.

An intense R&D activity is also taking place in the field of **Nuclear fission** energy to develop innovative options either for the production of **Energy ,** or for burning **Nuclear waste .**

In these areas, the physics of the reaction process, i.e : the history of the neutrons produced by the spallation process, as illustrated in fig. 3, implies basic nuclear physics studies (cross-sections, mass distribution of fission products, reaction models for neutron interaction etc...) in order to properly design a sub-critical reactor based on a high energy, high power proton driver .

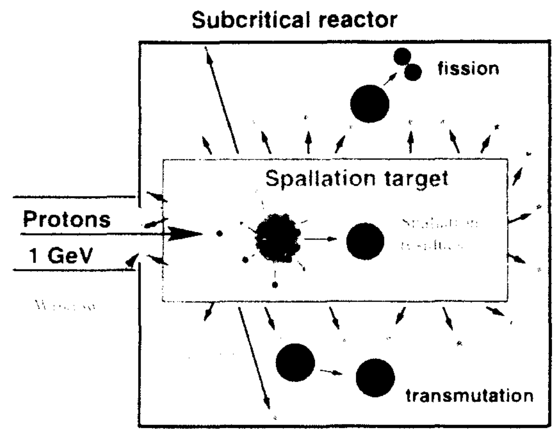

Fig.3 : Schematic representation of the spallation process induced by a 1 GeV proton beam on a thick lead target.

Nuclear energy and Nuclear waste transmutation induced by an Accelerator Driven System (ADS) requires a 1GeV, 10 mA, CW proton machine, e.g 10 MW power in the beam. In the discussions taking place on innovative options in fission energy based on ADS, the general consensus is that 1GeV 10 mA cyclotron option required considerable R&D and should be considered as a limit for this type of machine. Therefore, high intensity cyclotrons will not be the best choice for ADS and for neutron spallation sources but will remain very competitive in the area of radioisotope production as well as drivers for future ISOL-RIB facilities. Another area of important social impact is **Cancer therapy** and more precisely radiation therapy. In radiotherapy the tumour conformity of irradiation fields was increased to achieve higher cure rates, changing the radiation sources from low-energy X-rays to Megavolt gammay rays and finally to high-energy photons from electron accelerators.

The problem of radiation therapy is to maximise the tumour dose without harming the surrounding healthy tissues. With electromagnetic radiation, this is possible to a limited extent, in particular for deep-seated tumours.

The use of heavy particles in radiotherapy "**Hadrontherapy** " was motivated by a superior dose distribution in tissue compared to photons and electrons.

Protons have a well-defined range in tissue with no lateral scattering and a maximum dose deposition at the end of the track (Bragg peak). This is illustrated in fig.4.

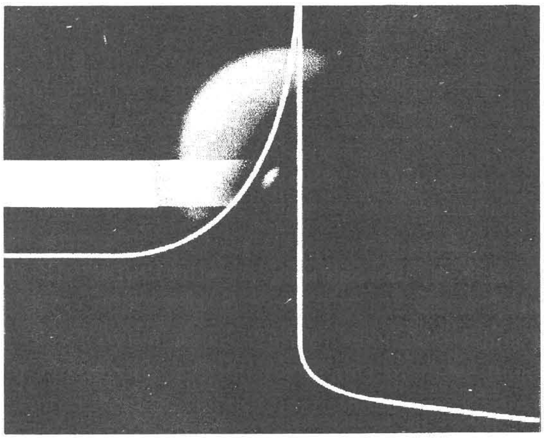

Fig.4 : The advantages of Hadrontherapy and conformal treatment for deep-seated tumours.

By varying the energy during the irradiation in a well-controlled manner, one can cover exactly the volume to be treated. To allow full flexibility in patient treatment, the accelerator should be coupled to an isocentric beam delivery system called "gantry".
At present, protontherapy centres are located in the United States, Russia, Europe, Japan and South Africa. Most of the clinical experience have been obtained in nuclear physics institutions which have devoted part of the accelerator time - **mainly cyclotrons** - to medical use.

To-day and more in the next 10 years, hospital-based facilities are needed as exemplified by the creation of Loma Linda (USA), Chiba (Japan), NPTC (USA) centres and the projects in France, Italy, Germany and Sweden.
Cyclotrons delivering proton beams of 70 to 230 MeV are proposed as the main accelerators in many of these planned new centres. In addition, new techniques are being developed like the use of heavier ion beams – C ,O, Ne at 400 MeV/n - the raster scan method for a precise application of the beam dose and the control of the beam position by the best on line diagnosis and imaging device, the positron emission tomography (PET).
The revolution in imaging applied to nuclear medecine associated to hospital-based cyclotons facilities are believed to have a strong impact in the fight against cancer.

IV. Conclusions :

Based on the perspectives of Nuclear Physics, high energy high intensity cyclotrons are considered as drivers for the next generation of RIB facilities. High transmission booster accelerators based on cyclotrons may also be part of the design of these future projects .
The combination of medium energy, hospital-based cyclotrons with a beam delivery gantry and beam scanning systems are promising tools in cancer therapy. Their developments should be strongly supported by the community of cyclotrons builders and nuclear physicists.