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NUCLEAR PHYSICS WITH RADIOACTIVE BEAMS

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1. INTRODUCTION

Following pioneering works in the beginning of the eighties (Dufour et al, 1981 - Nitschke, 1985 - Bimbot et al, 1985), there has been, since 1985, a growing interest in the physics involving beams of radioactive nuclei. With the increasing use of such beams and the development of many projects for their production all over the world (Bruandet et al, 1992 - Garret, 1992 - Morrissey, 1993), Nuclear Physics is going through the first steps of an evolution similar, in many aspects, to that which resulted from the onset of heavy ion physics in the early sixties.

2. RADIOACTIVE BEAM PRODUCTION.

Radioactive beams can be produced through two different and complementary ways which are the acceleration of radioactive nuclei immediately after their production, and the "in-flight" selection and purification of secondary beams issued from the fragmentation of high energy heavy ion beams.

2.1. Acceleration of radioactive nuclei.

The basic principle of this method, which is particularly suitable for obtaining low energy beams, consists in producing radioactive nuclei at rest, through a nuclear reaction induced with a primary beam in a primary target, in selecting the proper ones using an isotope separator, and accelerating them to the desired energy.

Figure 1: General layout of the radioactive ion beam facility at Louvain-la-Neuve.

The first radioactive beam of this type was a 0.65 MeV/u ^{13}N beam of $1.5 \cdot 10^8$ particle per second. It was obtained at Louvain-la-Neuve (Belgium) by coupling a low energy (15-30 MeV) proton cyclotron which delivered a high intensity beam (100 μA), with a heavy ion cyclotron, CYCLONE (Darquennes et al, 1990). The layout of this facility is shown in Fig. 1.

However, the most efficient methods to produce large amounts of radioactive nuclei are based on the use of spallation reactions induced with high energy protons. Several projects centered on this principle have been proposed all over the world (Bruandet et al, 1992 - Garret, 1992). Let us mention, for instance, the CERN-ISOLDE project, and the Isospin Laboratory in USA.

Figure 2: Layout of GANIL showing the implantation of the SPIRAL project.

A variant of this method will be used for the French project "SPIRAL" (Bex, 1994) under construction at GANIL (Caen). Here, the high intensity beams of "light" heavy ions (100 MeV/u ^{12}C to ^{36}Ar) from the GANIL set of cyclotrons will be used to produce the radioactive species through interaction with a primary target. Multicharged ions of these radioactive nuclei will be obtained using high efficiency ECR ion sources coupled with the production target. These ions will be accelerated up to 25 MeV/u using a specially designed variable energy cyclotron. The goal is to provide all beams with $A < 110$ in the energy range 2.7 to 25 MeV/u, making it possible to realise many experiments in the vicinity of the Coulomb barrier, and at energies significantly higher. Intensities ranging from 10^3 to 10^9 pps are expected. Note that this project is complementary of the SISSI device, which already provides secondary beams in the energy range 25-100 MeV/u (see below). A sketch of the GANIL layout showing the implantation of the SPIRAL project is presented in fig 2.

2.2. Production of secondary beams from projectile fragmentation.

This method is particularly suitable when the primary beam is an intermediate energy (30-100 MeV/u) or a high energy (GeV/u) heavy ion beam. At such energies, the projectile fragmentation reactions lead to a wide distribution of nuclei emitted forward with velocities close to that of the primary beam. Taking advantage of this effect, the secondary beams can be selected and driven to a secondary target using magnetic transport elements. Since the first Berkeley experiments, concerning exotic nucleus production (Viyogy et al, 1979), and medical applications (Alonso et al, 1979), several machines have produced secondary fragment beams, and most of them have built large acceptance spectrometers in that purpose (Bimbot, 1991). We shall focus here on two of them which are operating at GANIL, the LISE 3 spectrometer, and the SISSI solenoid associated to the ALPHA spectrometer.

* The LISE 3 spectrometer

at GANIL is able to select, among a wide variety of fragmentation products, a monoisotopic beam. Such a beam is characterized by three parameters: the atomic number Z which defines the element, the mass A which defines the isotope, and the energy E (or velocity v). Its purification is performed by three successive selections, (see fig 3) according to three different criteria (Mueller et al, 1990).

At each of the focal points the beam isotopic composition is analysed using a ΔE -time of flight method. An example of beam purification is given in fig 4 (Bimbot, 1991).

Figure 3 : Principle of the LISE 3 spectrometer. The first dipole operates a selection according to the magnetic rigidity $Br = k \cdot A/Q \cdot v$, i.e $Br = k \cdot A/Z \cdot v$ if the products are fully ionized. The achromatic degrader, placed between this dipole and the second one, and combined with this second dipole, selects the remaining isotopes according to the function A^3/Z^2 . Finally, the Wien filter (crossed magnetic and electrostatic fields), placed in the last part of the spectrometer, selects all ions having the same velocity.

*The SISSI superconducting solenoid has been installed at the entrance of the ALPHA spectrometer (see fig.2) in order to increase its angular acceptance and therefore its performances for secondary beam production. Originally built for improving the emittance and energy resolution of the primary GANIL beams, the ALPHA spectrometer was early used to select secondary beams produced in a target placed at its entrance. These beams could then be transported to any of the experimental rooms, and especially towards the SPEG spectrometer which was used (Gillibert et al, 1986) for many nuclear mass measurements (see below). However, the poor angular acceptance of the ALPHA spectrometer limited the intensity of the transmitted secondary beams. The addition of a pair of superconducting solenoidal lenses (Joubert et al, 1991) which became operational in 1994 made it possible to increase this transmission by a factor of about 30 for most of the secondary beams.

3. NUCLEAR PHYSICS WITH RADIOACTIVE BEAMS.

3.1. Identification and study of exotic nuclei.

Radioactive beams have mainly been used for identifying the exotic nuclei which they are made of and for studying their properties. Two categories of experiments may be considered: those which take advantage of the velocity of the nuclei which compose the beam, for identifying or transporting them, and those for which these new projectiles are used to induce nuclear reactions in a secondary target.

***Identification of new nuclei.** The nuclei which compose a radioactive beam are moving with a high velocity, and this property has extensively been used for their identification, using, for example, the

Figure 4: Secondary beam purification using the LISE 3 spectrometer. The isotopic composition of the beam is displayed: a) at the exit of the first dipole; b) after the achromatic degrader and second dipole; c) with no achromatic degrader, but using the velocity filter; and d) using the three selections.

Figure 5: Identification of the new isotope ^{100}Sn .

Top : using a 1095 MeV/u ^{124}Xe primary beam from the Darmstadt SIS and a Be target for the secondary beam production associated to the GSI fragment separator for selection and purification, and ^{100}Sn identification. (R. Schneider et al, 1994)

Bottom : using a 63 MeV/u ^{112}Sn primary beam from the GANIL accelerator and a Ni target, the SISI+ALPHA device for a first selection of the secondary beam, and the LISE 3 spectrometer for its purification and identification (Lewitowicz M. et al 1994)

ΔE -time-of-flight technique. In this technique, the nuclei are first selected according to their magnetic rigidity

$$Br = k \cdot v \cdot A/Q \quad (1)$$

i.e.

$$Br = k \cdot v \cdot A/Z \quad (2)$$

if the products are fully ionized ($Q=Z$).

Then, by measuring simultaneously their energy loss ΔE in a thin detector and their time-of-flight over a known path (i.e. their velocity), one obtains a non ambiguous identification, as shown in fig 4.

Many new isotopes have been identified using this technique (Viyogy et al, 1979 - Mueller et al, 1993) and the limits of the domain of bound nuclei have been reached for the lightest elements. This method of identification remains applicable up to the region of masses around 100, and a spectacular example is given by the recent discovery, performed almost simultaneously at GSI (Darmstadt) and at GANIL (Caen) of the doubly magic nucleus ^{100}Sn . (Schneider et al, 1994 - Lewitowicz et al, 1994) for which the identification diagrams are shown in Fig 5.

*Study of the properties of exotic nuclei . The use of radioactive beams is also an easy and fast method to transport exotic nuclei from the production target to a well shielded place where their radioactive properties (half-lives, level schemes) can be determined. Many results have been obtained using this technique (Mueller et al, 1993).

Finally, an interesting application of the time-of-flight technique is the direct measurement of the masses of exotic nuclei realised at GANIL (Gillibert et al, 1986) by coupling the ALPHA spectrometer, used to select the exotic secondary beams, with the high resolution SPEG spectrometer in which the magnetic rigidity of these beams can be accurately measured, together with their time-of-flight over 116 meters between the two spectrometers. This method has led to mass measurements for light nuclei , with a precision of the order of 0.5 MeV, which is quite good for testing the mass tables in this region of the isotope chart.

3.2. Study of exotic nuclei using secondary nuclear reactions. Neutron halos.

The most fascinating application of radioactive beams consists in using them to induce nuclear reactions in a secondary target. Here, an immense field is open. The goal of such experiments is to study either the structure of the exotic projectile, or the mechanism of the reaction involved. The first experiments have been oriented towards the study of the projectile structure.

Spectacular results have been obtained in this domain. They concern the structure of very neutron rich nuclei, at the limit of nuclear stability, for which a new phenomenon, the neutron halo, has been discovered.

The first puzzling results on this subject were obtained at Berkeley (Tanihata et al 1991), where the total interaction cross sections were measured for various stable and radioactive projectiles, and where an enhancement of the experimental values was found for very neutron rich projectiles, such as ^{11}Li , ^{14}Be , and ^{17}B .

Figure 6: Interaction radii for neutron rich isotopes of light elements from He to B. (after Tanihata et al, 1985).

Figure 7: Angular distributions of neutrons emitted from the collision of ^9Li and ^{11}Li nuclei with a gold target (from Anne et al, 1990).

This effect was interpreted as an increase of the nuclear radius for the corresponding isotopes (see fig.6). Later on, this result was explained by the presence of a two neutron halo. Among the experiments which helped to confirm this hypothesis, let us mention the study of ^{11}Li break-up performed at GANIL (Anne et al, 1990). In this experiment, the angular distributions of neutrons emitted after Coulomb or nuclear break-up of 30 MeV/u ^{11}Li projectiles into ^9Li +two neutrons were measured and compared to those obtained with a ^9Li beam of the same energy per nucleon. The results (fig. 7) show clearly that the angular distribution corresponding to ^{11}Li projectile is strongly peaked forward and more narrow than that corresponding to ^9Li ions.

The absolute break-up cross section is also higher for ^{11}Li , and all these data are consistent with a halo radius of about 12Fm, to be compared with the ^9Li radius of 2.5Fm, or to that of the uranium nucleus (7.5Fm)!

More recent experiments have also established the presence of a halo, made of only one neutron, in the ^{11}Be nucleus (Hansen, 1993). Many other halo-nuclei are supposed to exist among neutron rich nuclei and they represent a new class of objects of high theoretic interest.

3.3 Applications of radioactive beams for nuclear astrophysics.

The determination of reaction yields is of crucial importance for developing nucleosynthesis models in astrophysics. As many of the nuclear reactions which occur in the stars involve unstable nuclei, radioactive beams have also a considerable interest in this domain. For example, the first experiment performed with the ^{13}N radioactive beam at Louvain la Neuve was the measurement of the cross section for the capture reaction $^{13}\text{N}(p,\gamma)^{14}\text{O}$ at low energy. This reaction is indeed very important in the "hot" CNO cycle which takes place in massive stars. It has also been investigated by an indirect method using

high-energy ^{14}O beams produced through projectile fragmentation (Kiener et al, 1993). Several other reactions of interest in nuclear astrophysics have been studied or are under study, and a dedicated accelerator is being built at Louvain la Neuve.

4. TOWARDS MEDICAL APPLICATIONS....

Finally, radioactive beams have interesting applications in medicine (Bimbot, 1992), and especially in the field of heavy ion radiotherapy. Radiotherapy using proton beams, has been rapidly developing these last years, because it leads to a very precise deposition of the dose at the end point of the proton range (Bragg peak). The same "ballistic" qualities exist for heavy ion beams (carbon to neon), as it was shown during ten years of experimentation at Berkeley. Moreover, heavy ions may be more efficient than protons for the treatment of radioresistant tumors.(Castro., 1988). In this domain, the use of radioactive beams of positron emitters, such as ^{15}O or ^{19}Ne , associated with a simplified positron camera, as shown in fig 8, may be very useful to precise the exact position of the end point of the beam range, and to make sure that it coincides with the tumor location.

Figure 8: Use of a radioactive beam coupled with a positron camera for heavy ion radiotherapy.

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