REALISTIC PHYSICS PERSPECTIVES USING RADIOACTIVE BEAMS FROM SPIRAL AT GANIL*

G. DE FRANCE

GANIL, BP 5027, 14076 Caen Cedex 5, France

(Received January 8, 1999)

The majority of the large international community in nuclear physics is looking towards the use of radioactive ion beams to broaden the horizon of our understanding of the physics of the nucleus. In theory, the use of radioactive beams will open a new era in nuclear physics by allowing access to new isotopes and by increasing the production rates of nuclei which can presently only be populated with extremely low cross-sections or not at all. However the beam intensities as well as the rather low variety of accelerated species will be constraints at least at the start up of the new facilities. A realistic physics program at SPIRAL is described as well as the necessary experimental tools. These essentially consist in two major devices built in the framework of large european collaborations: the VAMOS spectrometer and the EXOGAM γ-ray array.

PACS numbers: 25.60.–t, 29.30.Kv, 23.50.+z, 23.90.+w

The enthousiasm around the field of physics with Radioactive Ion Beams (RIB) is obvious as illustrated by the number of laboratories developping such facilities all over the world. In theory, a vast range of nuclear physics will be opened up by using these new possibilities, leading in principle to a major step in the understanding of the nuleon-nucleon effective forces and, more generally, of nuclear structure. This is, at least, the statement of all the so-called "white papers" aiming at justifying the physics case underlying RIB facilities.

Scientific motivations of the RIB projects cover many topics such as halo nuclei and neutron (n) skins; mass measurements; evolution of the shell structure from symmetric to asymmetric nuclear matter; isospin symmetry and charge independance of the strong force; astrophysical processes (r- and rp-process); synthesis of the superheavy elements; exotic radioactivity; new

* Presented at the International Conference "Nuclear Physics Close to the Barrier", Warszawa, Poland, June 30–July 4, 1998.

type of pairing force; test of the standard model;*etc.* Each of these topics is facinating in itself and new constraints on various degrees of freedom of the existing nuclear models are anticipated.

However, the beam intensities expected from these future facilities are at least a factor 100 lower than those obtained with stable beams. This will put a severe limit (at the beginning in any case) on possible experiments.

Another aspect is our poor knowledge and experience of handling low energy RIB. Background radiation, for example, will be a major concern for gamma-ray spectroscopy as illustrated in the case of ^{19}Ne [1].

Last but not least, the various experimental conditions which will be met, will impose drastic constraints on the design of the future detection systems. At the same time, their performances must be very high in terms of efficiency, signal-to-noise ratio, acceptance, *etc.*

In this talk, I will try to stick to reality rather than desires. At the SPIRAL facility, currently under construction at GANIL, RIB will be available next year and a realistic physics program must be developped, taking into account beam intensities and species really available in the next few months. Thus I will talk of some selected topics which, I think, are feasible in a near future at GANIL and which will bring new milestones in nuclear structure understanding and modelling. I will also say a few words on two examples of extremely powerfull tools which will be available soon with stable and RIB: the gamma-ray array EXOGAM and the large acceptance spectrometer VAMOS.

1. Some physics with RIB

Realistic physics perspectives with RIB start with the minimum statistics required to determine within "reasonable" error bars an experimental observable over a "certain background". Not only the quantitative aspect is important but the qualitative too. In some cases, very few counts are enough to measure a quantity (decay studies; isotope identification;*etc.*) if the background is essentially zero. At the other extreme, many experiments require a very high statistics in a peak either to dominate a possibly huge background or to get a very precise measurement.

The lower the cross-section, the higher the beam intensity is required. This is illustrated in Fig. 1. Let us assume that for a given experiment, a reaction rate of 1 Hz is needed. With a cross-section of 1 barn and a target thickness of, let say 10^{19} atoms cm^{-2}, then realistically, we need a beam intensity of the order of 10^5 particle per second (pps). This limit of 1 Hz (assuming always a target thickness of 10^{19} atoms cm^{-2}) is indicated in Fig. 1 as well as the 0.1, 10, and 100 Hz borderlines. The cross sections of usual reaction mechanism are generally well known from stable beams.The domains for the most common ones are also roughly indicated.

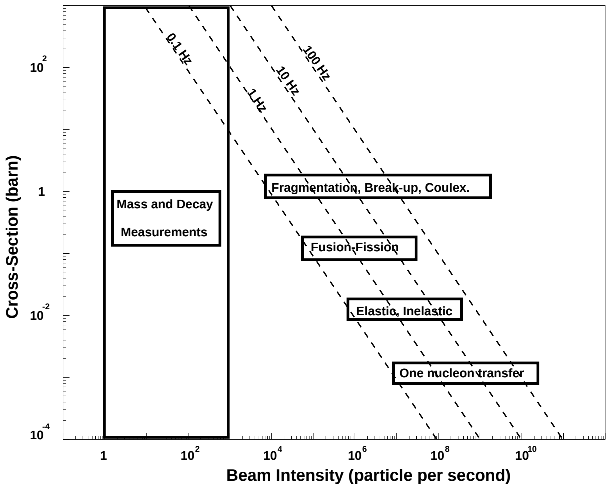

Fig. 1. Cross-sections as a function of beam intensity. A target thickness of 10^{19} atoms cm^{-2} is assumed to determine the the counting rates 0.1, 1, 10, and 100 Hz.

1.1. RIB today

RIB are already used today by several groups all over the world. Studies of the structure of exotic nuclei have been pioneered by the ISOLDE collaboration at CERN where superb results have been obtained, see for instance [2]. An alternative to the ISOL technique is to fragment a heavy ion projectile on a target at several tens of MeV per nucleon and to study the outcoming species either after implantation or following a secondary reaction.

Let me now focus on projectile fragmentation, currently performed since several years at GANIL, MSU, GSI, or RIKEN. The implantation technique at a final focus of a spectrometer has been extensively used since several years and lead to a rather coherent picture in the understanding of the production mechanism. This method has been applied with a great deal of success to look for new isotopes for example, as spectacularly illustrated with the identification of ^{100}Sn a few years ago [3, 4]. But it also allows study of nuclei in excited states when isomeric levels are populated in the fragmentation mechanism. The production of beams in isomeric states in the projectile fragmentation has been measured to be surprisingly high as discussed in [5, 6] and yield to the identification of many new isomers [7–9].

The typical examples for secondary reaction following the projectile fragmentation involve the electromagnetic interaction. The Coulomb dissociation of loosely bound nucleons (*e.g.* in halo nulei like ^{11}Be, see [11–14]) or very unstable nuclei (*e.g.* for astrophysical interests [10]), have been already studied. More recently, the Coulomb excitation of the exotic fragments into a heavy, high-Z target has been shown to be feasible. This allows us to have access to the first states (2^+) and to a good estimate of the quadrupole deformation via the B(E2) values. A complete description of this technique is given in [15, 16] and references therein.

Thus, physics using a radioactive beam is not a new field of physics. The new aspects in this field is related to the possibility to accelerate an exotic beam of high intensity, purity and good optical quality at a few MeV per nucleon. This is a major step forward when one wants to use other reaction mechanism to populate even more exotic nuclei for example. In the next section, I would try to give a taste of what will be feasible at GANIL-SPIRAL in a near future.

1.2. RIB tomorrow

The "realistic" aspect of the RIB is the use of beams which are delivered by the CIME cyclotron with a reasonable intensity and purity.

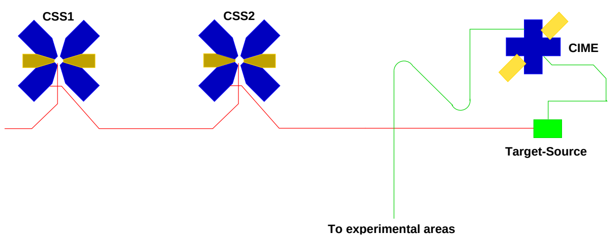

Fig. 2. Schematic layout of the SPIRAL facility comprising the two already existing cyclotrons (CSS1 and CSS2) as well as the target source where the exotic species are produced and extracted. They are then postaccelerated in the new CIME cyclotron and sent to the experimental areas after selection.

The SPIRAL facility (see the the schematic layout in Fig. 2) uses the primary beams delivered by the existing cyclotrons. The beam from the second cyclotron is fragmented onto a carbon target heated up to more than 2000° Celsius. In the first months of operation only noble gases will be produced and accelerated because their quasi-neutral chemical behaviour allows for a more efficient diffusion from the target. Hence they extraction from the target-source, the heart of the facility, is much easier as compared to metallic species for instance. Furthermore they are quite easily ionized in the ECR source leading to high charge state for acceleration in the CIME cyclotron. Therefore only reactions involving He, Ne, Ar, or Kr beams will be mentionned in this section. Also as a consequence, I will concentrate on physics of neutron-deficient nuclei.

1.2.1. Direct proton-emission

The α-radioactivity has been studied for many years but is a rather complex phenomenon to handle correctly from the theoretical point of view. First of all because it deals with prolate deformed nuclei for which the α-emission is clearly enhanced. This means that the basic physical problem is the tunneling of a charged particle through a deformed barrier. Secondly, before the α-particle is emitted, it has to pre-exist within the nuclei. This is a crucial input in the description of the tunneling process. A very natural way to simplify the problem is to use the proton (p) instead of the α-radioactivity. This is now possible because of the enhanced power of the new detectors which allow for a considerable reduction of the background and thus give access to very tiny cross sections. In particular, the combinations of recoil spectrometers and charged particle detectors make it possible to measure channels at the p-drip line as low as 0.2 μb [17]. Proton radioactivity is indeed a unique tool to obtain nuclear structure informations on nuclei located beyond the drip line. It is also a subtle mechanism which reveals the balance between centrifugal and Coulomb terms of the nuclear potential. Thus, p-radioactivity is a key process to understand more complex decay modes such as di-proton or α-radioactivity.

The first evidence for a p-radioactivity was found in 1970 [21] in the p-decay of ^{53m}Co. Since then, several cases have been found in the odd-Z nuclei of the $65 \leq \mathrm{Z} \leq 81$ region. Experimentally, direct proton emission gives access to angular momentum and spectroscopic factors. However, these latter have been determined with sometimes huge error bars. This is also an accurate tool to verify the various mass predictions via the measurement of the emitted p-energy (*i.e.* Q-value).

As pointed out in [18] spherical WKB approximation cannot reproduce the decay-rates of several p-emitter even though a qualitative agreement is obtained when using various simple theoretical approaches [20]. It is anyway very clear that the explicit treatment of deformation (*e.g.* Nilsson model) together with the measurement of (already existing in some cases [17]) deformed p-emitter half-lives gives valuable informations on single-proton orbitals. Rare earth-nuclei $Z \leq 66$ are predicted to be strongly prolate deformed [19]. Therefore a good test for the models would be to measure p-emitters in this mass region. The availability of radioactive Kr beams at GANIL will allow us to populate efficiently this mass region via fusion-evaporation reaction on neutron-deficient targets (Fig. 3).

The simultaneous emission of 2 protons (the di-proton or ^{2}He) is also an interesting open question. This has been predicted in the early 60's by Goldanskii [23] because the pairing energy between the 2 last protons enhance a di-proton radioactivity as compared to the single p-emission in even-Z p-rich nuclei. A 2 proton emission from the unbound nuclei has been

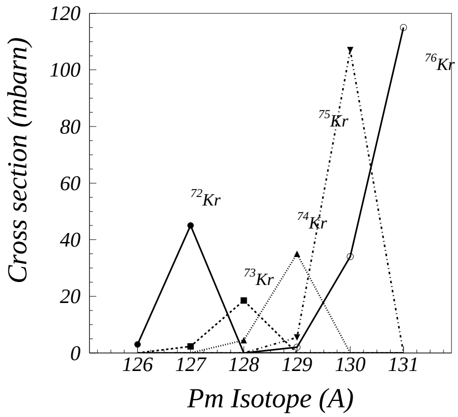

Fig. 3. Cross-sections calculated with the evapOR [22] Monte-Carlo code for a series of Pm isotopes using several Kr beams on a ^{58}Ni. In each case an excitation function have been calculated and the plotted values correspond to the maximum production of the given Pm isotope.

observed ^{12}O [24] (the other previously known example is ^{6}Be [26]). Using the 1995 atomic mass table from Audi and Wapstra [25] the Q_{1p} and Q_{2p} values are respectively ~ 1.97 and ~ 1.77 MeV. Hence the $2p$ is enhanced as compared to the $1p$ channel. However, both ^{12}O and ^{6}Be exhibit very small ^{2}He branching ratio, demonstrating that this phenomenon is more complex than anticipated such as a direct three-body breakup [26]. This shows, again, that the single-p radioactivity must be very well understood before going further away in more complex decay modes.

1.2.2. β-delayed multi-nucleon emission

Closely linked to the direct p-radioactivity is the β-delayed p-emission. For neutron deficient isotopes, this two-step decay is well known and statistical model are able to reproduce the p-energy spectra associated to this mechanism for the medium-mass and heavy nuclei(see for instance [27]). More exotic and much less clear is the β-delayed multi-proton emission such as β-$2p$, β-$3p$, *etc.* A very instructive example is the one of ^{31}Ar which has been studied in some details at GANIL [28] and also by the ISOLDE collaboration [29]. The β-$2p$ and β-$3p$ have been established. However the latter one remains to be confirmed since it has been reported in [28] but there is no evidence for such a channel in [29]. The 2 protons following the β-decay are emitted from the Isobaric Analog State (IAS) in ^{31}Ar and populate 3 distinct excited states $J^{\pi} = 1/2^{+}$, $3/2^{+}$ and $5/2^{+}$ in the daughter ^{29}P nucleus. Indication of a di-proton radiocativity have been deduced from angular correlation measurements between the 2 emitted protons and also from the continuous aspect of the p-energy spectrum. However, this statement remains clearly to be confirmed by new experiments and this is an excellent case for RIB. These decay studies performed with the fragmentation technique will be possible with SPIRAL. The intensity expected for ^{31}Ar *e.g.* should be more than one order larger than obtained at ISOLDE to reach more than 10 atoms of ^{31}Ar per second. This rate is enough to perform angular correlation measurement yielding the branching ratio of the ^{2}He vs sequential decay.

On the other side of the β-stability line, the β-n, β-$2n$, etc mechanism are of similar interest in terms of study of n correlations in these exotic radioactivities. Decay studies have the great advantage to generate background-free spectra and are therefore feasible with extremely low counting rates as already demonstrated with existing RIB production via projectile fragmentation. Thus the main difficulty in such experiments at SPIRAL will be to control the radioactive nature of the beam with shielding, coincidence techniques, *etc.* Useful beams for such studies will be in the first instance ^{8}He studied in coincidence with powerfull neutron detectors.

1.2.3. Halo studies

Halo nuclei have been extensively studied these last years both theoretically and experimentally. This is true especially for ^{6}He because it is approximated to the α-n-n three body system on a firm basis [30]. Furthermore ^{6}He beams with rather high intensities are produced already today. Conversely, more complex halo nuclei are very poorly known. However, as already said, the first exotic beams from SPIRAL will not allow the study of n-haloes but p-haloes can be studied. An efficient way to study halo nuclei is to use the huge cross-sections of the electromagnetic interaction via Coulomb dissociation (see [14] in the case of ^{11}Be for example). With cross-sections of the order of the barn it is possible to use beams with $\sim$ 100 or even less pps (see figure 1). Candidates for the first SPIRAL beams are ^{17,18}Ne in which an extended valence proton distribution is predicted [31, 32].

1.2.4. Shape changing/coexistence

Its is already a long time ago that shape coexistence and rapid shape changings have been predicted in the $N \sim Z \sim 40$ mass region [34]. "Heavy" $N = Z$ isotopes are of special interest. Self-conjugate nuclei have a very high degree of symmetry between neutron and proton dgrees of freedom. Nucleons occupy the same single particle orbitals and the associated wave-functions have large overlaps. Consequently, sudden structural evolutions are expected to occur when going from one nucleus to another. The active single particle orbitals in this mass region are the $1g_{9/2}$, $2p_{1/2}$, $1f_{5/2}$, and $2p_{3/2}$ and shape transitions will reflect their respective occupancy. In most of these nuclei, two minima are predicted in the potential energy surfaces, corresponding to oblate and prolate deformed shapes. When the ground-state is oblate, the prolate deformation is onset as soon as spin is larger than $2\hbar$ because the moment of inertia for a prolate shape is larger than the one obtained for an oblate nucleus, and hence, it is favored. Of the $N \sim Z \sim 40$ nuclei, Kr isotopes are of special interest because they will be produced at SPIRAL with quite a reasonable intensity. Very simple quantities, such as 2^+ and 4^+ state energies can be extracted from Coulomb excitation experiment which, again, has a large reaction cross-section. The other attractive aspect of such an experiment is the simplicity of the γ-ray spectrum. This makes of Coulomb excitation a judicious choice for the first experiments with RIB.

1.2.5. T=0, S=1 pairing

$N = Z$ nuclei have many other fascinating aspects. Related to isospin symmetry is the so-called $T = 0$ pairing. Usually nucleons are coupled in pair so that the total angular momentum of the pair is zero ($S = 0$). Furthermore, the curvature of the β-stability valley implies that n and p do not occupy the same single-particle orbitals. Thus the pairing interaction deals with nn and pp ($T = 1$) pairing. When $N = Z$ and especially for heavy nuclei, protons and neutrons occupy the same orbitals. This leads to a sizeable enhancement of the np-correlations and, among them, the np-pairing ($T = 0$) [35]. This form of pairing has not been observed experimentally but some evidence of its manifestation comes from binding energies. Additional pairing interactions translate into additional binding energy (the Wigner energy) and this is precisely what is observed as a spike in the isobaric mass parabola plotted as a function of $T_z = (N - Z)/2$ (see [36] and references therein). Only shell-model calculations taking into account the $T = 0$ pairing are able to reproduce this tendency [35]. Even more exotic is the $T = 0$, $S = 1$ pairing where the neutron and the proton are coupled at non-zero angular momentum, corresponding to a deformed np pair. Of course the best candidates to measure such an effect are odd-odd heavy $N = Z$ isotopes. An interesting quantity which can be used to measure this effect in rotational nuclei is the moment of inertia. Additionnal pairing also means a reduction of this experimentally easy-to-measure observable. Thus by measuring it in several neighbouring isotopes it is possible to extract the contribution of the $T = 0$ pairing. This can be done using fusion-evaporation with exotic He or Ne beams with $\sim 10^7$ pps. The more exotic the beam, the higher the cross-section to populate a given isotope as shown for the Krypton isotopes see Fig. 3. The balance between the loss in beam intensity to get more exotic species and the increase in cross-section is favorable in many cases. This solution has also the unique advantage to reduce the number of open reaction channels when the beam is more exotic.

2. Experimental equipment

The study of reactions induced by the radioactive beams from SPIRAL, requires new techniques and new demands on the design of the detectors. The constraints are severe from many aspects and are sometime different for two different devices. It is intended at GANIL to have a new gamma-ray array, EXOGAM, and a new magnetic spectrometer, VAMOS, to work with SPIRAL beams. I would like to describe both of them in some details.

2.1. The EXOGAM array

2.1.1. Design specifications

Radioactive beams impose new design considerations to a γ-ray spectrometer. The beam intensity, at least at the start up of the new facility, is expected to be much lower than with stable beams, factor of 10 or even 1000 lower. EXOGAM must therefore be designed to maximise the total photopeak efficiency. In maximising efficiency the spectrum quality must be maintained. The spectrum quality is determined by the peak to total ratio and energy and time resolution. The total efficiency measures the ability of the array to collect statistics. The spectrum quality measures the effectiveness of the array in isolating a single sequence or sequences of gamma-rays from a complex spectrum.

There will be a large variety of nuclear reactions using radioactive beams on which the design of a detection system must be based. The experimental conditions will be very different from one experiment to another in terms of γ-ray energy (from x-rays of tens of keV to γ-ray energies up to 5-6 MeV), of multiplicity (from one to $\sim$ 15 coincident photons); of recoil velocity (from zero to $\sim$ 10 % of light velocity); and of kinematics of the reaction mechanism (from recoiling fusion products emitted at $\sim 0°$ or scattered particles between $0°$ and $180°$). This variety means that the setup of the array must be adapted for each experiment. The radioactive nature of the beam is also a concern and shielding of the detectors becomes an important design criterion.

It is also clear that in addition to the detection of gamma radiation it will be vital to have ancillary detectors available to detect both light and heavy charged particles and neutrons.

2.1.2. Segmented CLOVER Ge detector

In order to meet all the design criteria the EXOGAM spectrometer will consist of an array of high resolution germanium detectors each surrounded by an escape suppression shield.

One composite and segmented detector is the segmented CLOVER detector [37]. It is made of four individual crystals each electronically divided into four regions. A schematic diagram of the crystals in a segmented CLOVER detector is shown in figure 4. The EXOGAM array will consist of such CLOVER detectors.

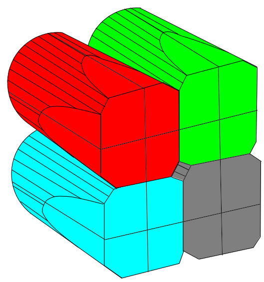

Fig. 4. The segmented CLOVER germanium detector crystals.

This segmentation is particularly useful when the emitting nuclei recoil with a large velocity since it allows a better determination of the interaction point of the γ ray in the detector. The detectors can be easily arranged in different configurations as will be shown later. This high degree of versatility is a very important design criterion as in the future the full gamut of nuclear reactions with stable and radioactive beams will be used for nuclear spectroscopy.

GEANT simulation calculations have been carried out to optimise the performances of CLOVER detectors for EXOGAM. The EXOGAM CLOVER will be based on the use of large Ge crystals, 60 mm in diameter and 90 mm long, before shaping. The photopeak efficiency of each CLOVER will be $\epsilon_p\omega \sim 12 \times 10^{-3}$ at 11 cm for a 1.3 MeV γ-ray. The segmentation of the crystals leads to a reduction by a factor of two of the Doppler broadening of the peak as compared to a non-segmented crystal.

2.2. Suppression shield for a segmented CLOVER Ge detector

Each segmented EXOGAM CLOVER Ge detector is surrounded by an escape suppression shield. The shield designed is based on a new concept in which the shield consists of several distinct elements, a backcatcher, a rear side element and a side shield, see figure 5. Designing suppression shields in this way, from individual elements, creates greater flexibility for different configurations.

The shields will be operated in two configurations. The first is with the back catcher and rear-side element, configuration A, and the second with the additional side elements, configuration B.

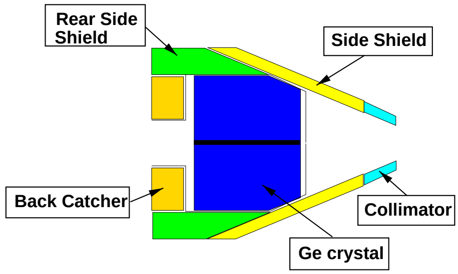

Fig. 5. The different elements of the BGO suppression shield for the segmented CLOVER Ge detectors (not to scale).

2.3. Segmented CLOVER arrays

The EXOGAM segmented CLOVERs can be arranged in different geometries. In all the geometries the suppression elements can be used in configurations A and B.

Configuration A is the close packed geometry where the Ge detectors can essentially touch at the front. Configuration B is the pulled back geometry in which the detectors are further from the target to allow for the inclusion of the additional side suppression elements. An array geometry for the

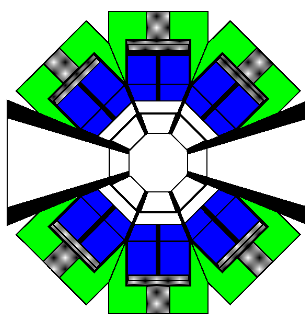

Fig. 6. A cross section through the 16 segmented CLOVER EXOGAM array.

CLOVERS to be as close as possible to the target, is with the detectors on the faces of a cube.

An array of 16 CLOVER detectors can be arranged. A cross section through this geometry in configuration A is shown in figure 6 and its isometric projection in figure 7. In configuration A the signals from adjacent Ge crystals can be summed to increase the efficiency. The calculated increase in efficiency is 6%.

The configurations, distances from the target, and performances for arrays of segmented CLOVERs are summarised in Table I.

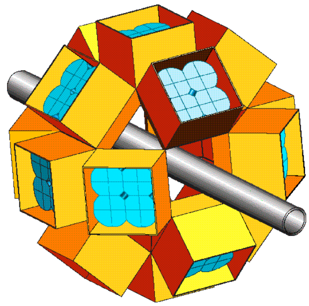

Fig. 7. The EXOGAM spectrometer with 16 segmented CLOVERs.

TABLE I

Summary of array geometries for segmented CLOVERs

Geometry	Shield conf.	Distance to target (mm)	Phot. eff. 662 keV	Phot. eff. 1.3 MeV	Peak/Total 662 keV	Peak/Total 1.3 MeV
Cube	B	68.3	0.15	0.10	0.72	0.60
16 det.	A	114.1	0.28	0.20	0.57	0.47
16 det.	B	147.4	0.17	0.12	0.72	0.60

The EXOGAM array will start its operation in 1999 with a few detectors and it will be completed to 16 by 2001.

2.4. The VAMOS spectrometer

The design specifications of the VAMOS spectrometer arise from the same constraints as it was for EXOGAM. The very low intensity of the radioactive beams imply new detection technique. However, when the channel of interest is several orders of magnitude lower than the dominant reaction channel, it is a real challenge to extract it. This is precisely the case, when using stable beams and a spectrometer it is essential to select efficiently the relevant events (see for example [38, 39]). With radioactive beams, and at least in the first years, the concern will be the weak but dominant channels. However, the efficiency of the recoil spectrometer strongly depends on the kinematics of the reaction. This is why inverse kinematics are generally choosen and yield to efficiencies up to ~ 20 %. The most intense beams from SPIRAL will be low A beams (typically $A \leq 40$). Hence standard reactions will be direct kinematics yielding large recoiling angle and low velocity. For these reasons, it appeared very soon that standard spectrometers are not adequate, at least in the case of fusion-evaporation reactions. Other reaction mechanism are expected to be used with VAMOS (VAriable MOde Spectrometer). One major field will be the elastic and inelastic scattering of the beam on p or n (extreme inverse kinematics) to study interaction potential properties and matter radii far from stability. In these experiments, the recoiling light particles are detected with dedicated devices and the beam must be rejected because the recoils are very close to 0°. Differential cross-section measurements and the influence of isospin on the reaction mechanism are also topics of great interest. A very powerfull method for these studies is the use of deep inelastic reactions leading to measurements of mass and charge as a function of the angular position of the spectrometer. Design specifications of the VAMOS are basically the same as for EXOGAM since it has to have a very large solid angle to get the efficiency and it has to be modular to cope with the various experimental conditions. The idea is to cumulate the quality of large acceptance, dispersive, and beam rejection devices. This has been done by designing a spectrometer comprising 2 quadrupoles, a velocity filter, and a dipole.

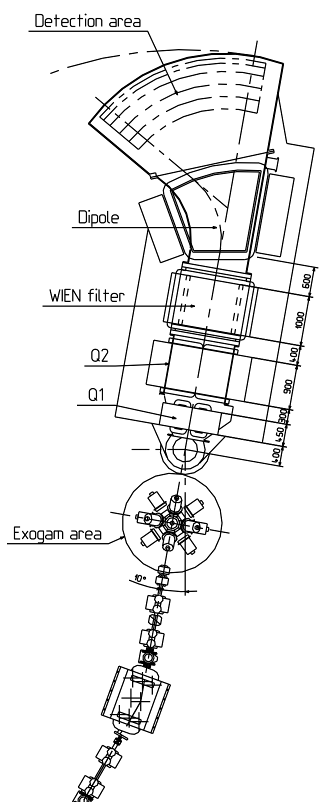

Fig. 8. The VAMOS spectrometer.

The angular acceptance will be $\pm$ 200 mr. The nominal dispersion is calculated to be $\sim$ 2% at the focal plane. The momentum acceptance will be $\pm$ 5%. Furthermore, it will be possible to rotate VAMOS by 90° around the target point with respect to the beam direction, opening up opportunities for the study of binary reactions (*e.g.* quasi-elastic and deep-inelastic reactions). These reactions will be powerful methods for producing nuclei inaccessible by other means. In such reactions, as already pointed out, the angular distribution of the reaction products is wide and their velocity large, increasing dramatically the widths of the γ-ray photopeaks. VAMOS will have the capability of measuring the speed and direction of identified products with high efficiency, and it will be possible to recover good resolution in the γ-ray spectra.

The minimum distance between the target point and the first quadrupole will be 40cm and can be extended to 140cm. These 2 situations gives the following characteristics for VAMOS: (solid angles, magnetic rigidity ($B\rho_{\max}$)) = (130 msr, 1.3 Tm) and (42 msr, 2.3 Tm), respectively.

It is planned that VAMOS will be located in the same experimental area as EXOGAM with EXOGAM at the target position. Therefore, the design of EXOGAM and of VAMOS will have to be compatible.

REFERENCES

[1] W.N. Catford *et al. Nucl. Instrum. Methods* **A371**, 449 (1996).

[2] B. Jonson *et al.*, *Nucl. Phys. News* **3**, 2 (1993); P. van Duppen to appear in Proc. of 2^{nd} Int. Conf. on Exotic Nuclei and Atomic Masses, AIP Publishing.

[3] M. Lewitowicz *et al.*, *Phys. Lett.* **B332**, 20 (1994).

[4] R. Schneider *et al.*, *Z. Phys.* **A348**, 241 (1994).

[5] B.M. Young *et al.*, *Phys. Lett.* **B311**, 22 (1993).

[6] K. Sümmerer *et al.*, *Phys. Rev.* **C42**, 2546 (1990).

[7] F.D. Bechetti *et al.*, *Phys. Rev.* **C42**, R801, (1990).

[8] J.L. Uzureau *et al.*, *Phys. Lett.* **B331**, 280 (1994).

[9] R. Grzywacz *et al.*, *Phys. Lett.* **B355**, 439 (1995).

[10] T. Motobayashi, *Nucl. Phys.* **A630**, 328c (1998).

[11] R. Anne *et al.*, *Phys. Lett.* **B304**, 55 (1993).

[12] S. Shimoura *et al.*, Proc. 6th Int. Conf. on Nuclei far from Sability and 9th Int. Conf. on Atomic Masses and Fundamental Constants, R. Neugart and A. Wöhr, IOP Publishing, 1992, p. 271.

[13] K. Ieki *et al.*, *Phys. Rev. Lett.* **70**, 6 (1993).

[14] T. Nakamura *et al.*, *Phys. Lett.* **B331**, 296 (1994).

[15] H. Scheit *et al.*, *Phys. Rev. Lett.* **77**, 3967 (1996).

[16] F. Azaiez and O. Sorlin, *Nucl. Phys. News* **8**, 3 (1998).

[17] C.N. Davids *et al.*, *Phys. Rev.* **C55**, 2255 (1997).

[18] C.N. Davids, NPA630, 321c (1997).

[19] P. Möller, J.R. Nix, W.D.Myers, W.J. Swiatecki, *At. Data. Nucl. Data. Tables* **59**, 185 (1995).

[20] S. Aberg, P. B. Semmes, W. Nazarewicz *Phys. Rev.* **C56**, 1762 (1997) and references therein for specific models.

[21] K.P. Jackson *et al.*, *Phys. Lett.* **B33**, 281 (1970); J. Cerny *et al.*, *Phys. Lett.* **B33**, 284 (1970).

[22] N.G. Nicolis, J.R. Beene, unpublished.

[23] V.I. Goldanskii, *Nucl. Phys.* **19**, 482 (1960).

[24] R.A. Kryger *et al.*, *Phys. Rev. Lett.* **74**, 860 (1995).

[25] G. Audi and A.H. Wapstra, *Nucl. Phys.* **A595**, 409 (1995).

[26] O.V. Bochkarev *et al.*, *Sov. J. Nucl. Phys.* **55**, 955 (1992).

[27] J. Hardy *et al.*, Proc. Int. Conf. on Nuclei far from Stability, Helsingor, CERN81-09, 217 (1981).

[28] D. Bazin *et al.*, *Phys. Rev.* **C45**, 69 (1992).

[29] I. Mukha *et al.*, *Nucl. Phys.* **A630**, 394c (1998).

[30] M.V. Zhukov *et al.*, *Nucl. Phys.* **A533**, 428 (1991).

[31] N.K. Timofeyuk *et al.*, *Nucl. Phys.* **600**, 1 (1996).

[32] A. Ozawa *et al.*, *Phys. Lett.* **B334**, 18 (1994).

[33] I. Thomson and M.V. Zhuhkov, *Phys. Rev.* **C53**, 708 (1996).

[34] W. Nazarewicz *et al.*, *Nucl. Phys.* **A435**, 397 (1985).

[35] W. Satula *et al.*, *Phys. Lett.* **B407**, 103 (1997).

[36] N. Zeldes in Handbook of Nuclear Properties, eds. D. Poenaru and W. Greiner, Clarendon Press, Oxford, 13 (1996).

[37] G. Duchêne *et al.*, submitted to *Nucl. Instrum. Methods.*

[38] P.J. Ennis *et al.*, *Nucl. Phys.* **A535**, 392 (1991).

[39] W. Gelletly *et al.*, *Phys. Lett.* **B253**, 283 (1991).