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PRODUCTION OF NUCLEI FAR FROM THE BETA STABILITY LINE USING INTERMEDIATE-ENERGY HEAVY IONS

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Résumé - La production de noyaux exotiques à l'aide des ions lourds aux énergies intermédiaires est passée en revue. Les différents mécanismes de production, essentiellement la fragmentation du projectile et les réactions de transfert, sont présentées ainsi que les premiers résultats.

Summary - The production of far unstable nuclei using heavy ion accelerators in the intermediate energy domain is reviewed. The various mechanisms responsible for the production of exotic species, mainly the projectile fragmentation and transfer reactions, are discussed, and the first experimental results presented.

INTRODUCTION

The production and study of nuclei far from stability has become one of the main goals of nuclear physics over the last decade /1-5/. If the existence of about 2200 nuclides has been confirmed, a total of 7000 isotopes are predicted to be bound in their ground-states. But the ultimate goal is probably not to produce them all.

The ambition of nuclear physics is to get finally a good description of nuclear matter through a unique elementary interaction, by using self consistent theories. Looking at nuclei far from stability may help to go in that direction. The same motivation which leads us to study hot nuclear matter near some critical temperature, should lead us also to study cold nuclear matter under extreme conditions with respect to the N/Z ratio. The most extreme N/Z ratios of nuclear ground states, accessible to experiments, are those at the border of nuclear stability, that is near the proton and neutron drip lines. These nuclides are those labelled "exotic" in this paper. Up to now, these limits have been reached for only the very light elements, the difficulty arising from the very sharp decrease of both production cross sections and lifetimes when moving away from stability.

Besides this first aim, mapping the drip lines, there are strong motivations to get a broad systematic study of the main properties of nuclei far from stability by varying the neutron and proton number over a very large scale. This provides challenging tests of semi-empirical models constructed near the stability and more self-consistent nuclear models. A good example is the discovery of a new region of deformation at N = 20, looking at the whole series of Na isotopes /6/. Such measurements may concern half-lives, masses, energy of the 2+ state, particle decay modes as β delayed neutron or proton emission or even more exotic decay modes as proton radioactivity. For these very exotic species, the quite large energy release for β-decay may allow a more precise study of the weak force. Finally, it is worth noticing the interplay between astrophysics and nuclear physics, connected for example to an improved understanding of the nucleosynthesis process /7/.
Up to now, various projectiles have been used to produce nuclei far from stability: neutrons, high and intermediate energy protons, low energy heavy ions /3,5,7-9/, relativistic heavy ions /10-13/. One of the most powerful method is based on spallation, fragmentation and fission reactions of heavy targets induced by protons as it is done for example at the ISOLDE facility /14/. In this paper, I shall discuss some of the advantages and limitations of these methods. My prime interest, however, will be to demonstrate that intermediate energy heavy-ions can be a powerful tool for studying cold matter with very unusual N/Z ratios. I shall restrict the discussion to the production of new isotopes in the light region \((Z < 40)\) as it appears to be the most easily accessible region for the existing facilities. In this first section, the various reaction mechanisms susceptible to produce exotic species by means of intermediate-energy heavy ion beams will be reviewed. A simple model will be presented which could be useful to make predictions for the production of exotic isotopes as well as secondary beams /15/. The related tools are briefly discussed in section II. In section III, measured and extrapolated production rates of intermediate energy heavy ion reactions are compared to those obtained at ion source based on-line separators. Finally, results obtained at GANIL for exotic nuclei will be discussed in section IV.

I - COMPETING REACTION MECHANISMS

In the low energy region, and as far as heavy ions are concerned, at least three processes have been used extensively for producing exotic nuclei: fusion followed by evaporation for central collisions, deep inelastic and two-body transfer reactions for peripheral collisions /3/. The situation is quite different at intermediate energies where the competing mechanisms (which are of interest in this paper) are mainly those arising from peripheral collisions, i.e. transfer reactions into continuum states /16-17/ and the so-called fragmentation process /18-20/. The latter is by far the dominant process and in many respects resembles very much the one observed with relativistic heavy-ions which has been proved to be also a good tool to produce very neutron rich species /10-13/. As several contributions to this conference are focused on this mechanism /20,21/, I shall just recall the main characteristics which are of direct interest for the production of exotic isotopes and for defining the experimental equipments:

i) The projectile-like fragments (PLF) are emitted with a velocity very close to the beam velocity. (Only a small shift is observed resulting from the friction force due to the binding energy of the abraded nucleons). At first order the momentum distributions can be reproduced using the Goldhaber approach, the width of the distribution being expressed by the relation:

\[
\sigma = \sigma_0 \frac{A_F (A_p - A_F)}{A_p - 1}
\]

where \(A_p\) and \(A_F\) stand respectively for the fragment and projectile mass, \(\sigma_0\) is constant over the whole mass range and close to 90 MeV/c.

ii) The angular distribution is strongly forward peaked and may be roughly calculated assuming an isotropic distribution in the projectile rest frame. In such a fast abrasion process, one expects the isotopic distribution of the outgoing fragments to be dominated by the isospin asymmetry of the projectile; more neutron-rich will be the projectile, more neutron-rich will be the reaction products. [This has been checked already at relativistic energies comparing \(^{40}\text{Ar}\) and \(^{48}\text{Ca}\) projectiles /11/]. A characteristic feature in this energy range is the substantial role of the neutron excess of the target for the neutron excess of the PLF in general and of the very neutron rich fragments in particular /22,23/. The most plausible explanation for this effect is the occurrence of nucleon-nucleon collisions in the overlap zone: combining the existence of a neutron skin in heavy targets with the high \(\sigma_{np}\) scattering cross sections between 20 and 100 MeV/u tends to increase the N/Z ratio of the PLF over that of the projectile /24/.

During this fragmentation process, it appears the PLF remain not much excited, as shown by recent exclusive experiments /25/. One may therefore reasonably estimate
the excitation energy of the primary PLF by the excess surface energy of the abraded fragments. Typical values range between 30 MeV for the reaction Ca + Ta and 50 MeV for Kr + Ta.

A simple abrasion-ablation model has been used for comparison with the measured data. It is a geometrical model where the mass distribution is calculated under purely geometrical considerations on the degree of overlap between the two interacting nuclei. Then the charge distribution is deduced assuming zero-point motion of the giant dipole resonance in the projectile /26/. Starting from the above mentioned estimate for the excitation energy of the PLF, the deexcitation stage, which plays a major role for determining the eventual production of very unstable nuclei, is calculated using the code LILITA /27/ and the predicted masses of Uno and Yamada /28/. This deexcitation is calculated for all primary products (i.e. around 280 for an Ar induced reaction) and the final mass and charge distributions deduced. Results of such a calculation are shown in fig. 1 for the system 44 A.MeV Ar + Ta and compared with experimental results obtained at LISE on this system /29/ (closed circles) and those from a very similar system, 44 A.MeV Ar + Au /22/ (open circles).

Results of such a calculation are shown in fig. 1 for the system 44 A.MeV Ar + Ta and compared with experimental results obtained at LISE on this system /29/ (closed circles) and those from a very similar system, 44 A.MeV Ar + Au /22/ (open circles).

The agreement is quite satisfactory for the peaks of the distributions (production cross sections 1 to 100 mb) and is surprisingly good for the most neutron rich isotopes observed! For the latter, the cross sections have been deduced from measurements performed at zero degree with a somewhat small efficiency (\( < 10^{-2} \)) and are therefore subject to large error bars (for more details, see section III).

The influence of the N/Z ratio of the projectile on the final mass distributions of the PLF is exemplified in fig. 2 for \(^{40}\)Ca, \(^{40}\)Ar and \(^{48}\)Ca induced reactions and Z = 14 products. [It should be noted that the cross section for the most probable isotope of a given Z is about 5 times higher than the one measured with high energy protons].

Besides this fragmentation channel, the transfer reactions are surely a promising way in some very specific cases, essentially for producing proton-rich nuclei. However one should keep in mind that it is limited to a few nucleon transfer (stripping or pick-up). The great interest lies in the fact that the momentum dispersion is much smaller than for the fragmentation products /23,30/ and the angular distribution is also peaked at very forward angles. Appreciable cross sections measured, even at the Fermi energies, lead to think that it could also be a very good tool for preparing secondary beams with high production rates. This has been effectively shown by Bimbot et al /31-32/ in Ar (and O) induced reactions where \(^{39}\)Ar, \(^{38}\)Ar and \(^{41}\)K have been obtained with production rates as high as 6 \(10^{-5}\) (with respect to the beam intensity).
It appears more difficult to answer the question of the effectiveness of central collisions at these energies. Let us mention the use of inverted kinematics in fusion reactions that would help to get a strong focusing of the recoiling products and the existence of a multifragmentation process where the target breaks into many pieces might well be another way to produce light neutron rich fragments.

Finally, as we do not know precisely what's occurring for heavier projectiles as Kr or Xe, we should remain open for surprises, especially those offering new production ways for exotic nuclei. (First results obtained with a Kr beam will be presented later on in this paper).

II - THE TOOLS

The main properties of these PLF, i.e. forward peaked angular distributions and a rather broad momentum width peaked near the beam velocity, are evidently very favourable for applying the technique of recoil separation. Let us mention the 0° LISE magnetic analyser /33/, the SPEG spectrometer at GANIL /34/, the RPMS /35/ (reaction product mass separator) at MSU. As an example, the 0° LISE spectrometer is shown in Fig. 3. It has an angular acceptance of 1 mrad and essentially consists of two identical dipoles; the first one is used as a dispersive element whereas the second one gives the necessary compensation to the dispersion in the first element. With such a system, one gets at the achromatic focal plane a double achromatism in angle and in position. The maximum rigidity acceptance is ± 2.5%. Moreover, the optical properties of LISE are conserved even in the presence of a thick energy degrader between the two dipoles. In that case, the first dipole provides the A/Z analysis whereas the Z dependance of the energy loss in the degrader, allows a selection of a given isotope at the focal point. The latter method is discussed in F. Hubert's paper /36/ and also by R. Bimbot et al /32/. I want to emphasize that this powerful method is essential for production of secondary beam with a high purity, and also for providing conditions for spectroscopic decay studies of PLF products.

Fig. 2 - Calculated final distributions for Z = 14 isotopes produced with 3 different projectiles. The influence of the N/Z ratio of the projectile appears very clearly [E_{inc} = 44 MeV/u, Ta target].

An on line mass separator has been tested at GANIL /37/ and target as well as projectile fragmentation have been looked for. The observed production rates were however...
too limited to allow spectroscopic studies.

Finally, other tools such as an He jet system should be useful for example to look for incomplete fusion reactions.

III - PRODUCTION RATES

In section I, it has been shown that quite high cross sections can be reached with intermediate energy heavy ions. However the only really meaningful parameter is the production rate (in atoms per second) at which a given isotope can be effectively measured. This rate determines the kind of study one is able to undertake: roughly speaking, 1 atom per hour may be enough to prove the existence of a new isotope, 1 to 10 per minute is necessary to get the half-life and more than 1 per second to deduce the first spectroscopic information.

The production rate $I_m$ is expressed by the following relation:

$$I_m = \sigma \cdot I \cdot N \cdot R$$

where $\sigma$ is the production cross section, $I$ the beam intensity (atoms/s), $N$ the target thickness (atoms/cm$^2$) and $R$ the efficiency of the experimental device. Typical cross sections at the Fermi energies have been given in fig. 1 and 2. The beam intensity available at GANIL is ranging from $4.10^{11}$s$^{-1}$ for an Ar beam down to $5.10^{10}$s$^{-1}$ for a heavier beam as $^{86}$Kr. Target thicknesses range between 0.1 and 0.5 g/cm$^2$. The efficiency $R$ is directly related to the spectrometer. A typical example is shown in fig. 4 for the reactions $^{58}$Ni + $^{58}$Ni and $^{40}$Ca + $^{58}$Ni at 55 MeV/u (with a target thickness of 0.1 g/cm$^2$). It takes into account the angular distribution of the products (assuming an isotropic distribution in the rest frame of the projectile), the angular acceptance of LISE, the energy spread due to the reaction mechanism (expression 1), the energy loss in the target /38/ and the rigidity acceptance of the spectrometer. This figure shows clearly that the efficiency is maximum for the products which mass is close to the projectile mass and therefore demonstrates than one given projectile defines one optimum region of study.

![Fig. 4 - The efficiency R of the LISE spectrometer is strongly depending on both the PLF' mass and the nature of the projectile. For both projectiles, a 100 mg/cm$^2$ Ni target is considered in the calculations. For more details on this calculation, see text.](image)

Typical expected production rates, at the focal point of LISE, are plotted in fig. 5-6 for the reactions 77 A.MeV Ar + Ta and 55 A.MeV $^{58}$Ni + $^{58}$Ni. [This calculation is using the model described in section I which has been shown to reproduce with a rather good accuracy the observed cross sections for the most probable isotopes and to some extend also for very neutron rich ones in Ar induced reactions]. From these results, two conclusions can readily be drawn:

1) the most probable isotopes for a given Z are produced with quite high rates, specially with Ar projectiles: $10^9$s$^{-1}$ $^{30}$Al, $3.10^9$s$^{-1}$ $^{35}$P. Even higher rates are predicted for products closer to the beam.

Table I gives the results of the calculation for masses 35 and 36 compared to the measurements of Bimbot et al /31/ in the reaction 44 A.MeV Ar + Be. The agreement, within a factor 3 or 4, is quite satisfactory. This calculation, based on a fragmentation model fails in predicting the high rates for fragments very close to the projectile originating mainly from transfer reactions (see results in table I for nuclides as $^{39}$Ar or $^{41}$K resulting from 1 neutron and 1 proton pick-up).
Fig. 5 - Typical production rates (in atoms s\(^{-1}\)) expected at the focal point of the LISE spectrometer with an \(^{40}\)Ar projectile [The rigidity aperture is \(\pm 0.5\%\)].

Fig. 6 - Same as fig. 5 for a \(^{58}\)Ni projectile [The rigidity aperture is \(\pm 0.5\%\)].

ii) Rather high production rates are expected for several unknown exotic nuclides or others for which we have almost no spectroscopic information. Moreover, these examples show that the neutron drip line is within the reach of the experimentalist for the light elements (\(Z < 8\)), as the proton drip line should be reached up to \(Z = 28\) using \(^{40}\)Ca and \(^{56}\)Ni projectiles.

Table I - The intensities (with respect to the primary beam intensity \(I_0\)) of secondary beams produced in the reaction 44 A.MeV Ar + Be (ref. 31) are compared to the fragmentation calculations.

<table>
<thead>
<tr>
<th>Secondary beam</th>
<th>(^{34})S</th>
<th>(^{35})S</th>
<th>(^{36})S</th>
<th>(^{36})Cl</th>
<th>(^{37})Cl</th>
<th>(^{39})Cl</th>
<th>(^{39})Ar</th>
</tr>
</thead>
<tbody>
<tr>
<td>((I/I_0)) Experiment</td>
<td>(2.8 \times 10^{-6})</td>
<td>(3.10^{-6})</td>
<td>(6.10^{-6})</td>
<td>(2.10^{-6})</td>
<td>(8.10^{-6})</td>
<td>(3.10^{-5})</td>
<td>(5.10^{-5})</td>
</tr>
<tr>
<td>((I/I_0)) Calculation</td>
<td>(3.1 \times 10^{-6})</td>
<td>(1.2 \times 10^{-5})</td>
<td>(2.2 \times 10^{-5})</td>
<td>(3.10^{-6})</td>
<td>(3.5 \times 10^{-5})</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

How could these rates compete with other existing methods. Let us first discuss neutron-rich isotopes and take as an example the results obtained with low-energy heavy ions at GSI. An example of the yields measured at the GSI on line mass separator is shown in fig. 7 for the reaction 7.5 A.MeV \(^{82}\)Se + \(^{186}\)W /39,40/. This may be compared to preliminary results of a recent experiment performed at LISE using the reaction 43 A.MeV \(^{86}\)Kr + \(^{197}\)Au /41/. During these measurements, the magnetic rigidity of the LISE spectrometer was swept over a large range in order to properly measure complete isotopic distributions of PLF at 0°. Fig. 8 shows for \(Z = 26, 28\) the measured production rates \(I_m\) for the optimal \(B_p\) setting of each isotope [i.e. the one corresponding to the most probable momentum of the ejectile]. As this experiment was performed with a thin target (2 mg/cm\(^2\)) and a very small rigidity aperture (\(\pm 0.25\%\)), one may then reasonably expect to increase the rates by a factor 200 in future experiments with thicker targets and larger momentum acceptance (see right scale in fig. 8). A surprising result is the broadening, observed for the isotopic distributions as compared to those obtained with lighter
projectiles as Ar or Ca. A broad mass (or isospin projection range $T_z$) is covered e.g. between $^{53}\text{Ni}$ ($T_z = -3/2$) and $^{72}\text{Ni}$ ($T_z + 8$). Comparing fig. 7 and 8 show that intermediate energy heavy ions may compete favourably for the production of neutron rich isotopes. On the proton-rich side, the situation does not seem to be equally favourable for intermediate energy projectiles, since fusion-evaporation reactions appear to offer favourable production conditions except for very short lived nuclides. [e.g. 200 atoms/s for $T_z = -1$, 150 ms $^{48}\text{Mn}$ from $^{12}\text{C}$ ($^{40}\text{Ca}, p3n$) reactions /42/]. For lighter elements ($Z < 10$) the very neutron rich isotopes cannot be formed easily by any low-energy mechanism and fragmentation reactions are surely by far superior.

Fig. 7 - Experimental yields of reaction products observed with the reaction 7.5 A MeV $^{82}\text{Se} + \text{W}$ with the GSI on-line mass separator (ref. 39,40).

The situation is different with high energy protons where, in principle, spallation, fission and fragmentation reactions with a heavy target are a very powerful tool to produce exotic isotopes over a broad mass range. The use of much thicker targets (typically 100 g/cm$^2$) and higher primary beam intensities (typically $10^{13}$/s$^{-1}$) result in the very high yields available at the ISOLDE facility [e.g. a production of 500 atoms/s for $T_z = -2$, 98 ms $^{32}\text{Ar}$]. There are however, also limitations to the application of ion-source based on-line separators, which do not exist with magnetic recoil spectrometers at the Fermi energy. They are due to the rather long and $Z$ dependant delay times, connected with the operation of an ion source, which limit measurements at the edges of the stability in general and become very stringent in case of very short periods ($T_1/2 < \text{few ms}$). These efficiencies are very high for the long-lived alkali isotopes (R ~ 1), but are strongly reduced for elements as Fe, Co, Ni or even more for elements as N (R ~ $10^{-4}$). However, for many elements, it remains the most powerful method, with more experimental improvements expected to occur in the near future /14,43/.

Fig. 8 - Preliminary yields $I_m$ measured for Fe and Ni isotopes in the LISE spectrometer through the reaction 43 A MeV $^{86}\text{Kr} + \text{Au}$. Results were obtained with a 2 mg/cm$^2$ thick target and a rigidity aperture of $\pm$ 0.25 %. In addition, estimated intensities $I_e$ are given, which one might reach using a 50 mg/cm$^2$ Au target and a rigidity aperture of $\pm$ 2.5 %. An example of the measured charge state distribution is given for $^{62}\text{Ni}$ (ref. 41).
In conclusion, it appears that 0° magnetic spectrometers with Fermi-energy heavy ion beams show a lead over other methods for investigating extremely short-lived, far unstable nuclei with \( A < 70 \). The advantages are obviously the fast collection time (< 200 ns), the absence of Z selectivity a priori (i.e. without intermediate degrader) and the possibility of introducing mass and charge selectivity by degrader techniques /44/. The main limitations arise from the use of rather thin targets (< 0.3 - 0.5 g/cm²), the mass dependence of the transmission, both effects restricting the production rates, and from the appearance of uncompletely stripped PLF using very heavy beams (see the example of a charge state distribution for \( Z = 28 \) in Fig. 8). However it appears clearly that there are strong needs for systematic studies of production conditions under 0° which are relevant to heavy ion reaction mechanism as well as atomic physics. For instance the broad isotopic distribution observed in \(^{80}\)Kr induced reaction cannot be reproduced using the fragmentation model described above (fig. 8) and might rather indicate the occurrence of a break-up of an excited Kr-like fragment. Several groups have already emphasized the appearance of new behaviours with such heavy beams /45,46/.

IV - EXPERIMENTAL RESULTS

IV.1 - Towards the frontiers of stability

IV.1.1 - Identification techniques

The LISE spectrometer, which has been already described in section II, implicitly defines how we can achieve the identification of the products. The flight time of the PLF is measured between the target and the final focal point of LISE (\( l = 18 \) m). At this point standard solid state detectors ensure the Z identification by usual \( E_\text{A} - AE \) techniques. Combined information from the telescope, the time of flight (TOF) and the magnetic rigidity setting allows in principle an overdetermination of the fragment mass and atomic number. Depending on the beam, the overall time resolution (between the RF and telescope signals) for the 18 m flight path is ranging between 0.2 and 1 %. A Z resolution of \( \Delta Z/Z \sim 1 \% \) is easily achieved.

The identification of the products is evident when looking at the bidimensional plot (fig. 9) representing the TOF (proportional to A/Z) versus Z. It exhibits characteristic curves, each of them related to a given \( T_2 \). The line of constant TOF corresponds to A/Z = 2, \( T_2 = 0 \), N = Z self-conjugate nuclei and the absence of well known unbound isotopes as \( ^{8}\)Be, \( ^{9}\)B and \( ^{16}\)F allows for an unambiguous identification.

IV.1.2 - Towards the neutron drip line

Two different projectiles have been used up to now to emphasize the production of neutron-rich isotopes : 44 A MeV \(^{40}\)Ar, 33 and 43 A MeV \(^{86}\)Kr projectiles. As mentioned before, the rate at which the neutron-rich isotopes are produced is much higher when using a neutron-rich target. Comparing Ta and Be targets shows a difference of several orders of magnitude for the production of very neutron-rich species /19/.

Fig. 9 - A typical two dimensional plot of events in the diagram Z versus time of flight (for more details, see text).
Results of the Ar experiments /29,47/ are shown in fig. 10. They can be summarized as follows: the existence of four new isotopes $^{22}\text{C}$, $^{23}\text{N}$, $^{29}\text{Ne}$, $^{30}\text{Ne}$, the absence of $^{21}\text{C}$, $^{18}\text{B}$ and the confirmation of the existence of $^{19}\text{B}$ already seen by Musser and Stevenson /13/ at the Bevalac. Moreover the particle unstability of $^{250}$ is very likely. These results call for two remarks:

i) the neutron-drip line has been reached up to $Z = 7$ according to all existing mass formula.

ii) The somewhat surprising identification of $^{29}\text{Ne}$, which was predicted unbound by almost all mass predictions. On the other hand Uno and Yamada /28/ predict an increasing particle stability in the Ne region (even Ne isotopes are predicted to be bound up to $^{38}\text{Ne}$). The observation of $^{29}\text{Ne}$ illustrates clearly that a simple determination of the bound character of an isotope can provide already a test of the mass formulas. The production of such neutron-rich isotopes might be very interesting for future spectroscopic studies as HF calculations /48-49/ indicate the onset of a new deformation region, most apparent for $^{32}\text{Ne}$. It seems however very difficult to go further off the stability line with an Ar projectile; nuclides such as $^{26}\text{O}$ or $^{32}\text{Ne}$ might, however, be within the reach of experiments with very neutron-rich projectiles such as $^{48}\text{Ca}$ (see section I).

iii) The observed cross sections for these very n-rich products are in rather good agreement with the calculations presented in section I (black circles in fig. 1 are the estimated experimental total cross sections assuming an isotropic angular distribution in the projectile rest frame). It shows the good sensitivity of the measurement as cross sections as low as 50 pb can be measured.

Fig. 10 - Mass histograms of neutron rich isotopes for the light elements obtained in the reaction 44 A.MeV Ar + Ta with the LISE spectrometer. (As the rigidity was set to optimize the production of very exotic isotopes, the distributions do not reflect the entire isotopic distribution for a given $Z$ (ref. 29,47)).

Extending earlier investigations based on deep inelastic /9,50/ and multinucleon transfer reactions /7,40/, 14 new nuclides in the region $18 < Z < 30$ have been observed /51/ for the first time in the reaction 33 A.MeV $^{86}\text{Kr}$ + Ti and preliminary results with the reaction 43 A.MeV $^{86}\text{Kr}$ + Au indicate the bound character of $^{71,72}\text{Ni}$ (see fig. 8) /41/. Obviously, these new isotopes are ranging far away the neutron drip-line. However, the production rates of neutron-rich species are expected to increase considerably if the extrapolation of the recent Kr + Au results, displayed in fig. 8, hold true; this is very encouraging for future spectroscopic studies as $\beta$-delayed neutron emission in this mass region which is in
the neighbourhood of the \( N = 40 \) shell and moreover of a great interest for astrophysics [77].

On the other hand, the isotope \( ^{67}\text{Fe} \), which was observed in LISE experiments for the first time, could be produced with the rate of 0.5 \( \text{s}^{-1} \) in future experiments (see fig. 8). This isotope could be a good candidate for the observation of neutron radioactivity as shown by calculations of Peker et al. [52] which predict the neutron emission from a high spin isomeric state. (However no experimental result is presently available concerning the angular momentum transfer in these fragmentation reactions). Obviously medium-heavy projectiles as \( ^{76}\text{Ge}, \ ^{82}\text{Se} \) and \( ^{86}\text{Kr} \) are very promising for future spectroscopic studies of neutron-rich isotopes with \( 18 < Z < 30 \); above \( Z = 30 \), further experiments with heavier beams such as Xe are needed to decide whether or not, conventional neutron-induced fission is becoming a more performing production process.

IV.1.3 - Towards the proton drip line

In the same way neutron-rich projectiles have been used for producing neutron-rich nuclides, the proton drip line has been investigated using proton-rich projectiles [53]. Two projectiles have been used so far: \( ^{77}\text{A.Fe} \) \( ^{40}\text{Ca} \) and very recently \( ^{55}\text{A.MeV} \) \( ^{88}\text{W} \). In both cases a quite neutron deficient target was used (\( ^{58}\text{Ni} \)) in order to enhance the production rate of proton-rich nuclei.

The most outstanding result is the clear evidence for the bound character of the \( T_z = -5/2 \) series: \( ^{23}\text{Si}, \ ^{27}\text{S}, \ ^{31}\text{Ar} \) and \( ^{35}\text{Ca} \) as shown in fig. 11. \( ^{35}\text{Ca} \) was first identified by its \( \beta \) delayed \( 2\pi \) activity [54]. Owing to the steepness of the valley of \( \beta \)-stability on the proton-rich side and sometimes some remaining background events one must be cautious before making definite statement on whether or not the drip line has been reached up to \( Z = 20 \) [55]. Fig. 12 shows for the series of nuclides with \( T_z = -3, -5/2, -2, -3/2 \) the predicted binding energies \( S_{1p}, S_{2p} \), calculated using the charge symmetry formula of Garvey and Kelson [56] as done by Janecke using the most recent experimental masses. From these predictions [58], one may then reasonably consider the proton drip line to be mapped experimentally up to \( Z = 20 \). The only possible exception could be \( ^{22}\text{Si} \) predicted to be bound against \( 2\pi \) emission by only 16 KeV ! On the other hand, the observation of \( ^{31}\text{Ar} \), predicted to be unbound by 180 KeV against direct \( 2\pi \) emission is particularly interesting as it may be a candidate for looking for this novel type of radioactivity. Such a decay has been discussed long time ago by Goldansky [59] and later on by Janecke [60]. A better candidate (i.e., higher \( Q_{2\pi} \) value, less \( \beta \)-decay competition) for the \( 2\pi \) radioactivity could be \( ^{39}\text{Ti} \), predicted to be unbound against \( 2\pi \) emission by 600 KeV. Unfortunately, it was not observed even with a \( ^{58}\text{Ni} \) projectile.

Preliminary results concerning the use of this \( ^{58}\text{Ni} \) beam indicate the bound character (lifetime \( 200 \) ns) of \( ^{43}\text{V}, \ ^{46-47}\text{Mn}, \ ^{49}\text{Fe}, \ ^{50-52}\text{Co}, \ ^{52}\text{Ni} \) and \( ^{55-56}\text{Cu} \). (The latter were obtained with an Al target). The observation of these new Cu isotopes would demonstrate clearly the effectiveness of transfer reactions even at these
energies for producing exotic isotopes. These preliminary results would also indicate that the proton drip line has been reached for odd elements $Z = 23, 25, 27, 29$.

**IV.2 - Study of nuclear ground-state**

Besides the experimental proof of the existence of an exotic isotope, even at the drip-lines, one needs obviously to go further in our knowledge of this exotic nuclear matter. Several groups are presently working in this field using the accelerators available in the intermediate energy domain. F. Hubert et al. /61/ are studying $\beta$-$\gamma$ correlations in $n$-rich isotopes. They have demonstrated the efficiency of the LISE spectrometer associated with a degrader in the intermediate focal plane. Several nuclides have been studied ($8 < Z < 16$) and their half-lives deduced. These results as well as the method are discussed in F. Hubert's paper /36/.

An interesting tool for $\beta$-$n$ correlations has been used in an experiment with the $^{18}$O beam delivered by the CERN synchrocyclotron /62/. It consists of a $4\%$ neutron ball, a very high efficiency neutron detector which provides a precise measurement of the $n$ multiplicity. The $\beta$ delayed neutron emitter $^{15}$B has been investigated this way. This technique should allow a precise measurement of the branching ratios $P_{\text{on}}, P_{\text{1n}}, P_{\text{2n}}$.

Other $\beta$ decay measurements have been performed at the NSCL laboratory at MSU using the reaction product mass separator. The lifetimes of $^{14}$Be and $^{17}$C have been deduced along with 5 other isotopes /63/. They also measured the $\beta^+$ branching ratios of $^9$C to the states in the unbound nucleus $^9$B /64/.

Another fundamental property of the nucleus is the binding energy strongly related to single-particle and collective effects. Extended systematic measurements over a large number of isotopes may reveal new interesting trends. Such a program devoted to mass measurements has been recently started by Mittig et al. /65/ at GANIL. A very original method is presently used in which the SPEG spectrometer is coupled to a time of flight measurement over a very long flight path.

The mass is deduced from the well known relation:

$$Bp/v = m/Z$$

The target is located at the exit of the last cyclotron of the accelerator and the standard beam line is now used to transport the secondary beam up to the spectrometer. This provides a flight path of 116 m which, with a time resolution of 0.5 ns ensures a resolution $\Delta v/v \sim 5 \times 10^{-4}$. With a rigidity resolution of $10^{-4}$, the mass excess of several light neutron rich nuclides ($7 < Z < 9$) has been measured with an error close to 500 KeV. Resulting separation energies $S_{\text{on}}$ are plotted in fig. 13 for the series of $N$, $O$ and $F$ isotopes along with all existing experimental results and compared with the calculation of Uno and Yamada /28/ and Möller and Nix /66/. An interesting result is that the investigated neutron-rich isotopes of oxygen...
As far as the near future is concerning, we may conclude that the measured yields for nuclei far from stability are large enough to start extensive decay studies. In addition to \(^6\)\(\gamma\) and mass measurements, systematic studies of delayed neutron and proton emission can now be performed over a large mass and charge range. Moreover, somewhat more exotic behaviour should be looked for, as for instance \(^{2p}\) and neutron radioactivities. However, there is still a strong need for measuring production cross sections at 0° and further investigate the reaction mechanisms, especially for heavy beams. (It has been shown that Kr results already display some new behaviours). On the other hand, there is a lack of information on the charge state distributions for thick targets of various atomic numbers when using beams with \(Z > 30\). An improved knowledge of the experimental conditions might be useful to make possible the use of other tools such as He jet systems or on-line mass separators.

Several new other isotopes could be produced using medium heavy-ion beams with \(Z \leq 36\). Let us mention \(^{39}\)Ti using \(^{56}\)Fe projectile, \(^{260}\), \(^{32}\)Ne with \(^{40}\)Ca and neutron-rich species in the region 18 \(\leq Z \leq 30\) with \(^{82}\)Se or \(^{86}\)Kr beams. The later should allow to produce Ni isotopes may be up to the doubly magic nucleus \(^{78}\)Ni. These new results, together with those concerning mass and half-life measurements are summarized in fig. 14. These experiments have also demonstrated the effectiveness of this energy range in producing secondary beams with a quite high production rate.

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Upgraded facilities at GANIL and MSU will provide us in a few years with even heavier beams at sufficiently high energies. (For example 45 A MeV Xe and 35 A MeV Ta beams will be available at GANIL). New perspectives may be opened also at higher energies with the appearance of new facilities as the SIS project at GSI and Mimas at SATURNE.
Fig. 14 - Summary of experimental measurements performed with intermediate energy heavy ion projectiles [GANIL, MSU, CERN-SC] (for more details, see text).
The calculated drip lines are also shown as predicted by Uno and Yamada /28/ and Gorvey-Kelson formulae /56-58/. The labels 1, 2, 3 for half-life measurements correspond respectively to ref. 61, 63, 62.
For each Z, the two numbers refer to the last known isotope on both the neutron rich and the proton rich sides. Triangles indicate the bound character of new isotopes observed in the reaction 55 A.MeV $^{58}$Ni + $^{58}$Ni and 43 A.MeV $^{86}$Kr + Au (preliminary).

Finally, let us think of the possibility to get very high intensity beams (as high as $10^{14}$ s$^{-1}$) as presently under discussion for the GANIL accelerator. That may offer also completely new possibilities for producing secondary beams as well as for the decay study of nuclei very far from the $\beta$ stability line.

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