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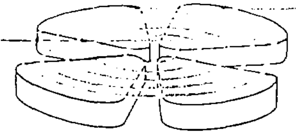

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LIGHT NUCLEI FAR FROM STABILITY : LIMITS AND PROPERTIES

by

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1. Why and how to study light exotic nuclei.

The production and the study of light nuclei either neutron- or proton-rich has benefited from several breakthroughs. Although the ingenuity of physicists often provided ad-hoc ways to produce a rare sought-after nuclear species, a few mechanisms were particularly prolific. Fission was for a long time the most efficient source of isotopes far from the valley of β-stability (Lysekil 1966). In the early 70's, deep inelastic collisions provided a new way to enrich the neutron number of light nuclei. Tens of new neutron-rich isotopes were observed (Artukh 1971, Volkov 1973). Two other mechanisms continously contributed to the steady increase in the number of known isotopes. Compound nucleus formation followed by the evaporation of some nucleons, mostly neutrons, is one of them. Well suited to the use of advanced spectroscopic methods, it keeps playing a major role in the study of exotic isotopes (Armbruster 1982, Roeckl 1983). Also target fragmentation, as induced by energetic projectiles, usually light (p, α, π, ...), associated with mass spectroscopy techniques, has been a rich source of results (Thibault 1981).

A few years ago, a new method appeared, potentially as general as those mentionned above. It uses the mechanism of projectile fragmentation. A heavy-ion projectile impinging on a target at high velocity, typically a few hundreds of MeV per nucleon, is likely to experience fragmentation. The Z and N distributions of these fragments, which are governed by statistics, allow observation of exotic nuclear species which could not be reached otherwise, as demonstrated in the pionneering work done at the Bevalac (Symons et al 1979, Westfall et al 1979).

The availability of new heavy-ion accelerators, with energies reaching 100 MeV per nucleon and intensities much higher than those obtainable at the Bevalac, opens a possibility to further extend that method. Fragmentation at, say, 50 MeV per nucleon is certainly not the clear process that makes up for the total reaction cross section at much higher energies. The momentum distribution of the fragments, which in first order results from the inner momenta of participant nucleons within the projectile, is relatively broader at GANIL than at Bevalac energies, hence the collection of fragments is less efficient. This distribution is further broadened by dissipation effects, reminiscent of low-energy mechanisms, which persist at a few tens of MeV per nucleon, as it is now well documented (Guerreau 1985). Yet the fact that the intensities available at GANIL for the projectiles of interest reach 5 x 10^{11}pps and are expected to increase over the years offers an unmatched opportunity to produce new exotic isotopes.

This raises the difficult question of determining which new isotopes, which of their properties are the most relevant to study. There are indeed some three or four thousands of bound isotopes vet unobserved and it is worthwhile assuring which of them can shed light on the fundamental properties of nuclei and can contribute to better the existing nuclear models. The analysis of the evolution of nuclear properties along a chain of isotopes of given Z might help clarify this question. Figure 1 presents the variation of log $T_{\frac{1}{2}}$ with the neutron number of isotopes. Several regions can be identified. For instance, it seems that the detailed study of one more nucleus on the long slope of region e, towards the neutron drip line, cannot be expected to bring any but local information.

One would expect more from two other types of research:

First, the exploration of new types of radioactivity should be pursued. In the latter years new exotic processes have been discovered. Among the most spectacular results is certainly proton radioactivity (Hoffmann 1984). Several new β-delayed emissions were also observed : two neutrons (Azuma et.al. 1979), two protons (Cable et al. 1983), three neutrons (Azuma et al. 1980, Langevin et al. 1981), triton (Langevin et al. 1984) and also β-delayed α emission from a neutron-rich isotope (Détraz et al. 1983). New radioactivities are now within experimental reach, as discussed below (§3). The wealth of information further gathered on the already known β-delayed proton -and even more, neutron-emission has led to realize that these are widespread processes, which rapidly dominate all decay processes far from β-stability (Klapdor et al. 1984) and hence play a major role in explosive stellar nucleosynthesis.

Second, it appears that a most fruitful contribution from the study of exotic nuclei would come from the knowledge of basic nuclear parameters on long series of isotopes. These parameters are for instance the values of the binding energies as obtained from mass measurements ; $T_{\frac{1}{2}}$ values ; β- delayed neutron emission probability (P_n) values ; excitation energies of the lowest 2^+ levels of even-even isotopes. Static properties such as magnetic moments or quadrupole deformations (Jacquinot and Klapisch 1979, Otten 1981) although difficult to measure systematically far from stability, are also of major importance. The point is that the reliable knowledge of such properties, even with a limited accuracy, provides a severe test of current models as long as it bears on large numbers of neighbouring isotopes.

2. Towards the proton and neutron drip lines

Knowing that an isotope is bound or not for proton or neutron emission puts a limit on its binding energy, and allows a comparison with the large number of theoretical mass predictions (Maripuu 1975). The fragmentation-like process of projectiles from GANIL has been used to push the limits of experimentally observed nuclei further toward the drip lines.

The prime requirement of such investigations is to detect and identify fast projectile fragments with as high an efficiency and as low a background as possible. A double magnetic system called LISE (Langevin and Anne 1985) was built to best meet this requirement. Fragments

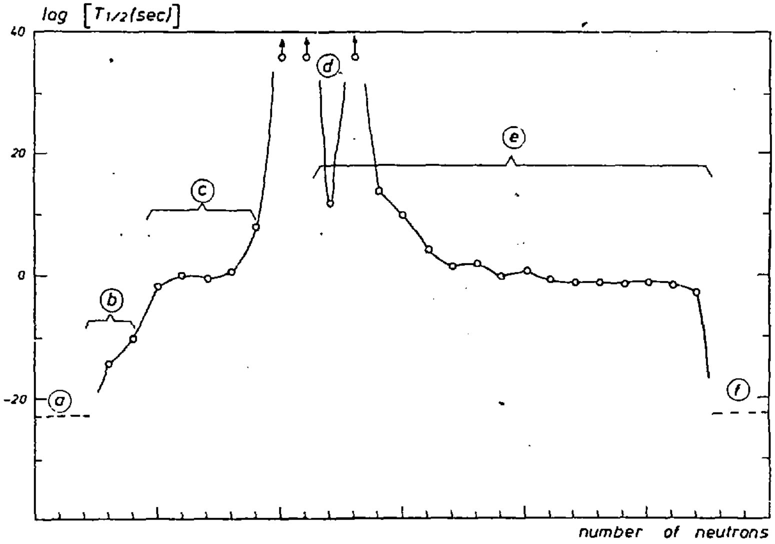

Fig. 1 Typical variation with N, the neutron number, of the radioactive half lives of isotopes of given Z. So-called stable nuclei (region d) have $T_{\frac{1}{2}}$ values of the order of magnitude of the proton half life itself for which only a lower limit is known. Furthermore the half lives of nuclei much heavier than ^{56}Fe are also limited by the fact that fission-like disintegration processes are open, even if it is with exceedingly long half lives (Sandulescu et al. 1985). If the nucleus is bound for hadron emission but can β-decay, $T_{\frac{1}{2}}$ ranges from 1 ms up, the shortest half life yet observed being 1.5 ms for ^{35}Na (Langevin et al. 1983 a). This corresponds to regions c and e, and these isotopes are usually said to "exist" or "to be bound". It is in these regions that a growing number of β-delayed emission processes have been observed (see text). At last if the nucleus is unbound for neutron emission, $T_{\frac{1}{2}}$ falls brutaly down to some 10^{-23} sec. A staggering odd-even effect can occur at the border of the neutron drip line. On the proton-rich side the fall from about 10^{-2}s to about 10^{-23}s is not as drastic due to the Coulomb barrier which inhibits the emission of low-energy protons. Thus, for available proton energies smaller than about 1 MeV (region b) proton radioactivity can take place and was actually observed (Hofmann 1984). That is also where two-proton radioactivity is expected. The limit between this region b and region a where unbound protons leave the nucleus before it is actually observed obviously depends upon detection techniques. Hence the limit between proton-active and proton-unbound nuclei cannot be but somewhat arbitrary. It should be emphasized that, for most Z values, except the very lowest ones, only a small fraction of this curve is known.

selected according to their A/Z values are collected in a low-background room by a triple-focusing system within the 5 % momentum acceptance of the magnetic system. Further fragment selection, accomplished by using an energy degrader between the two dipoles, has been successfully realized (Dufour et al. 1986 a).

In successive runs over the last two years, many new isotopes were observed. From an ^{40}Ar projectile, ^{23}N, ^{29}Ne, ^{30}Ne (Langevin et al. 1985) and even ^{22}C (Pougheon et al. 1936 a) were observed, while the unbound character of ^{21}C and ^{25}O was established. The fragmentation of neutron rich ^{86}Kr projectiles yielded fourteen new isotopes (Guillemaud-Mueller et al. 1985).

On the proton- rich side, the use of ^{40}Ca projectiles allowed the observation of Tz = - 5/2 isotopes, ^{23}Si, ^{27}S, ^{31}Ar and ^{35}Ca (Langevin et al 1986). At last a run with a ^{58}Ni beam was performed. Although the data analysis is not final, twelve new isotopes can already be reported (Pougheon et al. 1986 b)(fig.2).

As for the production yields, several informations came out of this work. The complexity of the reaction mechanism, at variance with the simple fragmentation process, was clearly established. For instance the influence of the neutron richness of the target was observed (Guerreau et al. 1983). Furthermore the large yields observed from transfer mechanisms, even at relatively high incident energy, definitely open new possibilities (see fig. 2). It also becomes clear that the maximum efficiency for yielding new isotopes far from the valley of β-stability is reached for Z-values not too much smaller than the Z-value of the projectile. Figure 2 shows a good example of that general trend which might be explained by the increasing surface excitation energy associated with an increasing size of the bite operated on the projectile, in the framework of the abrasion-ablation model. This increased excitation energy for lower Z values would indeed result in the evaporation of more nucleons when the quasi-projectile deexcites, hence to a return towards the valley of stability for the final cold nuclei.

There are at least indications that, with heavier projectiles, the fall of yields with increasing N for a given Z might be more moderate than the factor close to 10 which is observed for each step further away from stability in the case of lighter projectiles. This is possibly related to the onset of new reaction mechanisms, like fission for instance. An analysis of the yields observed, which is essential for determining the most efficient choice of the projectile, of its energy, and of the magnetic setting of LISE, is under way (Guerreau 1986).

The experimental results obtained so far yield useful informations on the proton and neutron drip lines. On the proton-rich side, the observation of the four Tz = - 5/2 nuclei allows to reach the drip line for most Z values up to Z = 20 (see fig.4). As shown in figure 1, the drip line is not as sharp on that side as on the neutron-rich one. Hence the so-called existence of a few light proton-rich nuclei is still open. A most interesting case concerns ^{22}Si since Garvey-Kelson calculations (Jänecke 1976) lead to a near-zero binding energy.

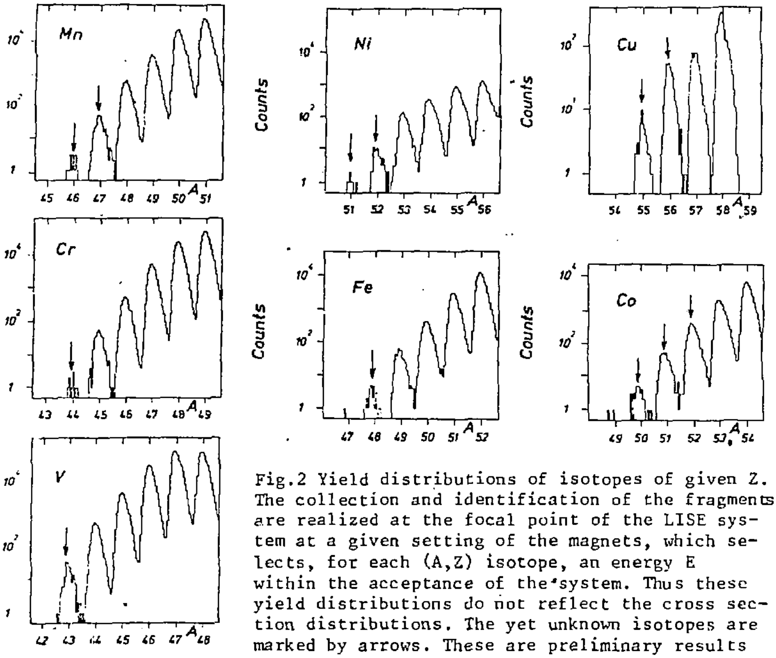

Fig.2 Yield distributions of isotopes of given Z. The collection and identification of the fragments are realized at the focal point of the LISE system at a given setting of the magnets, which selects, for each (A,Z) isotope, an energy E within the acceptance of the system. Thus these yield distributions do not reflect the cross section distributions. The yet unknown isotopes are marked by arrows. These are preliminary results from an on-going analysis of the data collected with a 55 A MeV ^{58}Ni beam from GANIL. Note that most new isotopes are obtained for elements with Z values only slightly smaller than the projectile one, and that Cu isotopes result from the addition of one proton to the projectile.

On the neutron-rich side, the neutron drip line appears to be reached all the way up to Z = 7 (Pougheon et al. 1986 a). The relevance of the type of results reported here is well illustrated by the case of ^{29}Ne that all mass predictions but one (Uno and Yamada 1982) found unbound and which was definitely observed (Langevin et al. 1985). It might be relevant to note that with Z = 10 and N = 19, this isotope, for which a binding energy larger than predicted by systematics or extrapolations is observed, lies very close to the Z = 11-12, N = 20 nuclei. This is an area of very strong deformation (Détraz 1981) at the expected location of a closed shell. That case indeed certainly provided a clear example of the unique and fundamental information on nuclear models that the study of exotic nuclei can contribute.

3. The search for new radioactivities

The concept of radioactivity has greatly benefited in the last few years of the discovery of new radioactive processes. Those have been mentionned above (§1). Some new ones might become attainable in the near future.

A very fascinating one would be two-proton radioactivity. Pairing energy effects make the binding energy of many even-Z proton-rich nuclei stronger against one-proton than two-protons emission. At the proton drip line it might happen that a nucleus is thus bound for one proton emission but is able to decay by the emission of two protons. This process was discussed long ago by Goldansii (1961, 1966) and Jänecke (1964). The probability of this emission is governed by barrier penetration which itself strongly depends upon the kinematics of the two protons. It is generally found that the configuration most likely to speed up the crossing of the barrier corresponds to two correlated protons equally sharing the available energy.

Some light nuclei which can be produced from GANIL projectiles are good candidates to exhibit 2p radioactivity. The negative binding energy (E_{2p}) should not lie below about - 0.8 or - 1 MeV so that the $T_{\frac{1}{2}}$ (2p) value is not so short as to make the nucleus decay before it is detected. And it should not lie above about - 0.3 or - 0.4 MeV so that the $T_{\frac{1}{2}}$ (2p) value is not that much longer than the competing $T_{\frac{1}{2}}$ (β) value as to make the 2 p branching ratio vanishingly small. Thus a narrow energy window, say $- 0.4 > E_{2p} > - 0.8$ MeV, exists for potential candidates to 2p radioactivity with Z values around 15 or 20.

The nucleus ^{31}Ar, recently produced with good statistics (Langevin et al. 1986) appears not to be unbound enough since Garvey Kelson calculations (Jänecke 1976) predict E_{2p} of the order of - 200 keV. One should yet remember that large deviations sometimes occur for new masses measured away from stability (Haustein 1984), so that 2p emission from ^{31}Ar cannot be ruled out. Another candidate is ^{39}Ti with a predicted - 700 keV 2p value, but which is still to be produced (see fig.2).

Candidates for neutron radioactivity were identified long ago by Pecker et al (1971) as long lived isomers with very high spin, among neutron-rich nuclei of the fp shell. The neutron radioactivity process depends drastically upon the difference between the energy locations of such a high-spin configuration and the neutron emission threshold. Thus precise predictions are particularly difficult. Yet such situations as found by Pecker et al are probably bound to occur. This makes the search for neutron radioactivity legitimate, even if difficult, especially since, among the candidates identified, some of them, such as ^{67}Fe, can be obtained at GANIL. It should be remembered that proton radioactivity was first observed from an isomeric state (Jackson 1970, Cerny 1970).

At last it seems that at least one more β-delayed particle emission process might be possible close to the proton drip line. It concerns ^{3}He emission and requires that the binding energy of ^{3}He in the daughter nucleus is significantly smaller than the Q_{β}-value of the parent nucleus. Energy windows of 3 MeV or more can be found for ^{22}Si, ^{27}S, ^{31}Ar, ^{35}Ca, ^{39}Ti or ^{43}Cr for example.

4. Mass measurements

The knowledge of the binding energy of a nucleus provides a stringent test of nuclear forces, especially in the case of exotic nuclei which have an unusual unbalance of protons and neutrons. Indeed predictions widely differ between themselves far from stability and, even with limited accuracy, experimental results are quite discriminatory and enlightening. The variation of the binding energy along a series of isotopes also reveals fundamental nuclear properties such as shell closure effects or onsets of deformation (Audi et al. 1979, Epherre et al. 1979).

Thus the fact that new isotopes are produced at GANIL with large yields opens the possibility of a fruitful and broad investigation of binding energies of light nuclei far from stability. The absolute measurement of the nuclear mass must be accomplished with an uncertainty much smaller than 1 MeV to provide useful information. For a nucleus of interest, all the collected events must then be free of spurious background counts, and the relative FWHM of the two parameters necessary to identify the isotope must be at most a few 10^{-4}. The accuracy on the peak centroid, a portion of the FWHM which decreases with increasing statistics, can then reach the required level of a few 10^{-5}.

A very powerful method to reach that goal has been developped at GANIL. The nature and energy of a fragment produced are extracted from two parameters known with a remarkably high accuracy. Its magnetic rigidity is measured by the SPEG spectrometer with a FWHM of 10^{-4} (Birien and Valero 1981). Its time of flight is determined along a flight path some 100 meters long since the target is exceptionally located near the exit of the second and last sector-separated cyclotron of GANIL, while the fragment is detected in the focal plane of SPEG. New mass values with accuracy better than 500 keV (fig.3) have already been reported (Gillibert et al. 1986) for $^{20-21}$N, ^{23}O, $^{24-25-26}$F and new data are being analyzed. They are expected to give improved results, with uncertainties around 200 keV, for some 12 new isotopes (Gillibert and Mittig 1986). They will bring new information on the behaviour of neutron-rich nuclei near N = 20, where the very strong deformation observed at Z = 11 (as mentionned in §2) seems to quickly disappear for increasing values of Z (Fifield 1985, Fifield 1986).

There is clearly there a concrete possibility of obtaining systematically the binding energy surface of light nuclei, which should stimulate theoretical efforts in this field.

A special attention should be directed to the case of neutron-rich isotopes with very low Z, especially since a calculation of their masses from shell-model or Hartree-Fock techniques is rather unreliable. Although the non-occurence of light neutral nuclei (Turkevich et al. 1977, De Boer et al. 1980) and the unbound character of ^{10}He (Volkov 1973) are supported by strong experimental evidence, the theoretical understanding of the nuclei close to the N-axis of the isotope chart is still limited. In this respect, the difficult mass measurements recently performed at Dubna (Belozyorov et al. 1985) for the unbound neutron-rich isotopes of hydrogen are very useful.

5. Other quantitative informations on exotic nuclei.

While a production yield of one nucleus per day might suffice to determine that an isotope exists, i. e. is bound, much higher yields are needed to derive quantitative informations about them. For an absolute measurement of its mass, as accomplished by the method described in the preceeding

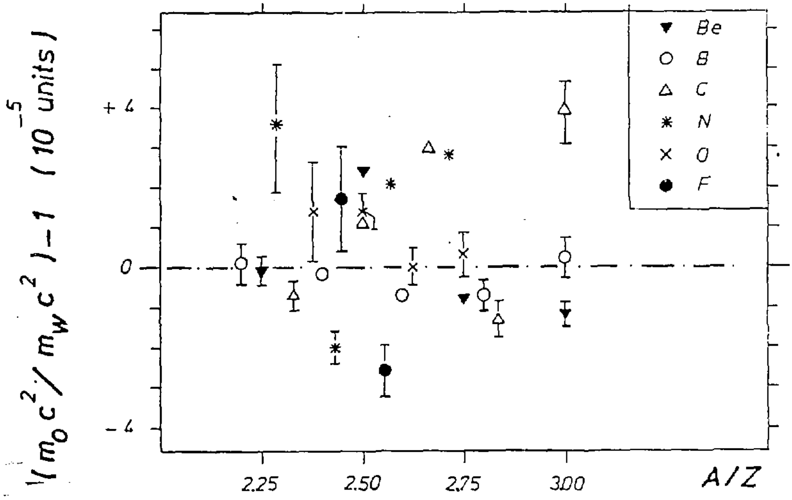

Fig. 3 An analysis of the deviation of the absolute masses of known nuclei as measured at GANIL where m_o refers to the measured value and m_w to the compilation by Wapstra and Audi (1985). This figure is extracted from Gillibert et al. (1986). The dispersion of the values around zero has a FWHM of 4 x 10^{-5}.

section, it is difficult to obtain accurate values if the yield is much lower than one nucleus per second. Some kind of simple γ spectroscopy still requires a yield two orders of magnitude higher. It also requires that the fragments selected by LISE according to their A/Z value be further selected to reduce the number of simultaneously collected nuclides in the same run. An energy degrader between the two dipoles provides such a second independent selection. It has been put to use by the Bordeaux group with excellent results (Dufour et al. 1986 a). Indeed, for the nuclei of interest, the energy-loss selection operates according to a $A^{2.5}/Z^{1.5}$ law which, combined with the magnetic selection which follows the A/Z law, drastically restricts the number of nuclear species collected at the focal plane of LISE. Although simple in its principles, this method requires considerable care to conserve the achromaticity properties of the instrument. Furthermore, changing charge states in the energy degrader might reduce its efficiency and considerably complicate its use for high-Z fragments. Yet, for nuclei up to about Z = 20, it has brought excellent results. The half lives and γ energies for the β-decay of thirteen new neutron-rich isotopes have been reported (Dufour et al. 1986), as far from stability as, e. g. ^{24}F, ^{25}Ne, ^{36}Si or ^{40}S (see fig. 4). A similar production mechanism, i. e. fragmentation, together with another type of isotope separation technique, has allowed to measure the half lives of the ^{14}Be and ^{17}C fragments from 30 A MeV ^{18}O projectiles at MSU(Curtin et al.1986).

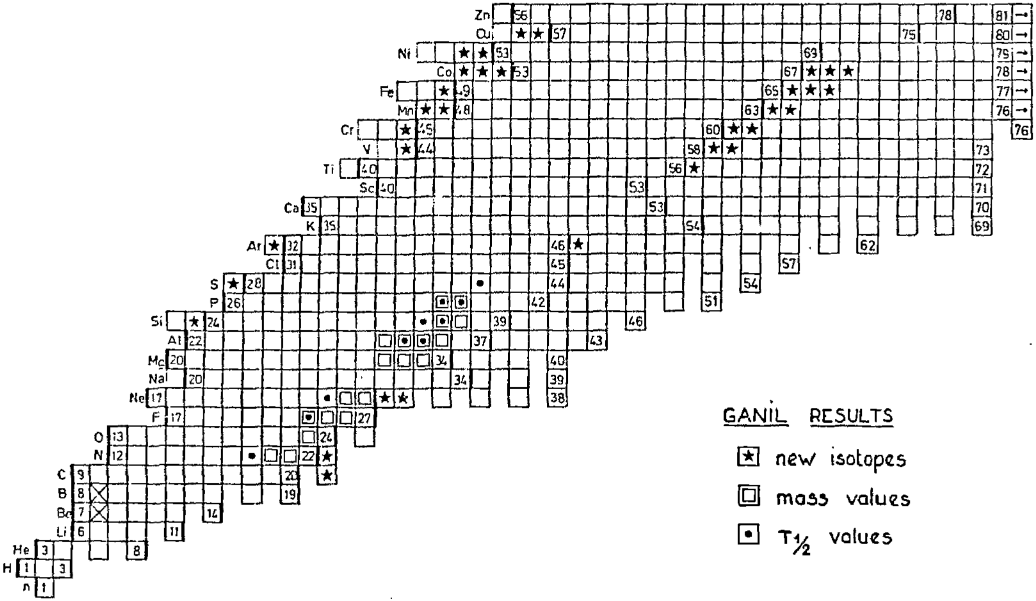

Fig.4 Chart of the light nuclei showing the results obtained at GANIL over the last two years. The thick lines indicate the limits of previously known isotopes. The neutron drip-line is predicted by Uno and Yamada (1982), and the proton-drip line is calculated by the Garvey-Kelson procedure (Jänecke 1976). The proton-rich isotopes represented by squares with dotted lines are those which are calculated to be only slightly unbound for p and 2p emission ($0 > S_p > -0.4$ MeV and $0 > S_{2p} > -0.8$ MeV) so that they are candidates for p and 2p radioactivities.

Some indications that isomeric states are formed can be and will be examined by this method. It is clear that in this region the occurence of shape or high-spin isomers would constitue a very valuable information.

The fruitfulness of such a systematic measurement of $T_{\frac{1}{2}}$ values should not be overlooked, since the comparison of the experimental trends with model calculations can bring new informations. For instance, $T_{\frac{1}{2}}$ measurements recently performed at GSI with the on-line mass spectrometer indicate a systematic over estimation of the half lives by the calculations, wether or not they include shell effects (Bosch et al. 1985), in the region of fp-shell neutron-rich nuclei. On the contrary, the $T_{\frac{1}{2}}$ values measured by the same group for neutron-rich nuclei in the rare-earth and radium regions agree well with the predictions.

Although they are only starting, two experimental programs launched at GANIL should be mentionned. Very proton- (or neutron-)rich isotopes have high probabilities of β-delayed proton (or neutron)emission. The study of these two processes is indeed of the highest importance : β-delayed proton emission brings direct information on the location of high-isospin isobaric states and on the quenching of the Gamow-Teller resonance (Bjornstad et al. 1985) ; β-delayed neutron emission provides overall informations on the location of shell-model configurations in the daughter nuclei (Langevin et al. 1983 b). Such studies can be performed with yields in excess of about 10 nuclei per second, which makes them practicable at GANIL for a large number of isotopes.

6. Summary

During the last two years, the fragmentation-like process of projectiles from the high-intensity beams of GANIL, with energies in the range of 40 to 80 MeV per nucleon, has produced scores of yet unknown isotopes. Their spectroscopic study has been undertaken (fig.4). This new powerful method should certainly allow to further extend the field of known nuclear properties away from the valley of β-stability. It can directly benefit from the use of new beams, such as ^{48}Ca, and from the improvement of accelerated intensities. Since fragmentation-like processes occur at energies well in excess of 30 or 35 MeV per nucleon, the higher energies planned for the heavier ions at MSU, GANIL and GSI will allow an extension of the region of known nuclei all the way up to uranium.

This certainly represents another breakthrough in the study of exotic nuclei. Yet, one should not overlook that well established methods can still bring results of the highest importance. In particular, the on-line isotope separators have the unique advantage of providing nuclei at rest, which opens the possibility of implementing the most effective spectroscopic techniques. And the deep inelastic collisions might still be the best suited tool in specific cases. The structure effects observed in ^{238}U induced dissipative collisions (Mayer et al. 1985) might favour the production of magic exotic nuclei such as the much sought-after ^{100}Sn.

It has been emphasized above that fruitful informations can be derived from the study of exotic nuclei if systematic measurements of the most basic properties are made for whole areas of the nuclidic chart. Examples were given of such result bearing on the mass, the $T_{\frac{1}{2}}$ value, the probability for β-delayed neutron emission, the γ energies. One more parameter might have been unduly neglected so far, the total reaction cross section

(Bruandet 1986) which yet brings unique information on the relative radii of isotopes and can be determined by simple techniques well suited to the canty yield of exotic nuclei. The recent results obtained at Berkeley (Tanihata et al. 1985) for the He and Li isotopes will obviously be extended to others.

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