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PROPERTIES OF LIGHT NUCLEI FAR FROM STABILITY

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Recent developments in the study of nuclei far from stability are presented with an emphasis on those properties which bring informations on correlations in nuclei.

§1. Introduction

Nuclei far from stability are no longer an experimental curiosity. After deep-inelastic reactions, high-energy proton-induced fragmentation, heavy-ion induced compound nucleus reactions, a new experimental opportunity has appeared in the last decade to strongly enhance the number of nuclear species opened to investigation. That is the fragmentation-like processes with the high intensity beams available at intermediate-energy heavy-ion accelerators such as GANIL. Tens of new nucleides are discovered (Fig. 1) with every new projectile used, such as ^{86}Kr (ref.1), ^{58}Ni (ref.2), ^{48}Ca (ref.3), to cite only but some of them. Were it not for the fact that the intensities of about 10^{12} ions per second available at GANIL are several orders of magnitude larger than those reached so far at accelerators of higher energy, the yields of fragmentation products at GANIL would be smaller since heavy-ion beams of high energy ($\sim$ 1 GeV/u) have attractive features (compared to lower energies) for producing exotic nuclei and studying them after separation in an energy-loss achromat. These features are : (i) large thickness of production target ; (ii) strong forward peaking for projectile fragments (high transmission in a 0° spectrometer) ; (iii) full stripping even for very heavy products (high charge-state yields, possibility for unambigious isotope assignment in an energy-loss achromat).

In this respect the forthcoming availability of a fragment recoil separator at the new SIS accelerator of GSI should open broader possibilities.

Yet one feature of reactions at energies ranging between about 30 to 100 MeV per nucleon, as available at GANIL, should maintain a very valuable advantage. It concerns the experimental possibility of studying the decay of exotic nuclei brought to rest, which is necessary in view of the long times (by nuclear or time-of-flight standards) involved in ß-decay. At GANIL energies only a few per cent of the nuclei brought to rest in the detecting telescope undergo a nuclear reaction which changes their nature. On the contrary, at GeV per nucleon energies, as much as 80% of them might be lost in such processes.

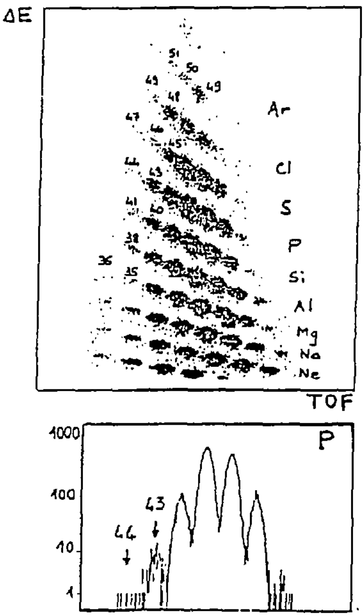

Fig. 1

Bidimensional representation of the projectile-like fragments from 55 Mev/u ^{48}Ca identified through Δ E vs. TOF (upper part). The fifteen new isotopes observed in this experiment are indicated with their mass number. The lower part shows, as an example, the mass spectrum of the phosphorous isotopes. Preliminary results from ref. 3.

That effect, together with the need of low-background measuring conditions, which implies an increase, soon to be prohibitive of concrete thickness around the detector area with increasing energy, might well make intermediate-energy reactions still a very valuable tool to study exotic nuclei in the years to come.

Indeed the study of these nuclei, and not just their observation, is the justification of their difficult production, since they offer the opportunity to investigate whether nuclear models, and the whole set of known nuclear properties, only apply to those nuclei, close to the valley of stability, from which they were elaborated, to examine whether they validly account for nuclear systems of very different isospin. Furthermore, spectroscopic studies very close to the proton or neutron drip-line should reveal new behaviours when binding energies tend to varish.

In this paper, recent developments relative to those uncommon properties of nuclei far from stability are reviewed, with an emphasis on light nuclei and on the information they offer on multiple-nucleon correlations.

§2. Binding energies

Theoritical predictions of binding energies, strongly constrained in the vicinity of the ß-stability line, tend to widely differ for more exotic isotopes.

The simple observation of a new nuclide, which implies that its half life is governed by ß-decay, i.e that it is bound for strong interaction, might sometimes bring an usefui information.

The relevance of this type of results is well illustrated by the case of ^{29}Ne that nearly all mass predictions found unbound and which was definitely observed by Langevin et al[4] at GANIL . It might be relevant to note that with Z = 10 and N = 19, this isotope, for which a binding energy larger than predicted by sytematics or extrapolations is observed, lies very close to the Z = 11-12, N = 20 nuclei. This is an area of very strong deformation[7] 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.

Yet the knowledge of nuclear binding energies can only come from mass measurements.

For nuclei near stability, the determination of the Q-value of transfer-reactions will give results of a very good precision. However, this method fails for nuclei very far from stability due to the very low cross-sections for multi-nucleon transfer reactions. The determination of the Q-value of ß-decay is problematic due to the non-discrete ß-spectrum and the need of knowledge of the decay scheme.

Thus if high enough production rates are obtained, the direct measurement of the mass has considerable advantages for nuclei very far from stability. However, the desired precision of mc^2 of less than 0.5 - 1 MeV, necessary to obtain crucial tests of the models, requires a precision of better than 2.10^{-5} for a mass 50 nucleus. This implies a high resolution measurement device, reasonable production rates of the nuclei of interest, and very low systematic errors.

One way to reach such a goal has been developped by W. Mittig and his coworkers at GANIL [5]. A direct and precise measurement of both the time of flight and the momentum of the fragments allow mass measurements with systematic errors smaller than 10^{-5}. As a result, the knowledge of nuclear mass has been extended for several isotopes with Z = 4 to 15. These results were compared to theoritical predictions. Empirical relations were seen to produce important errors in their extrapolation, even when a large number of free parameters is involved. Best agreement with the results was obtained for the shell-model calculation of Wildenthal et al [6], except for nuclei near N = 20 and N = 21 (Fig. 2).

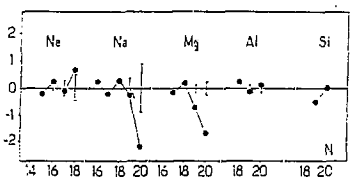

Fig. 2

Difference betwen the measured (ref. [5]) and the predicted (ref. [6]) mas excess values for five different elements of the sd shell as a function of the number of neutrons.

As mentionned above, this is precisely one well-documented case where the study of exotic nuclei sheds new light on established nuclear properties. Indeed far from being spherical as expected from the magic character of N = 20 nuclei ^{31}Na and ^{32}Mg appear very strongly deformed.

It is anticiped that the availability of a ^{48}Ca beam at GANIL will allow to measure the masses of neutron-richer isotopes, namely ^{32}Na and ^{33}Mg. It will become possible at last to check the pionnering and spectacular mass measurements [8] of Na isotopes performed some ten years ago.

This difficult and fundamental endeavour of mass measurement far from stability benefits from the fact that another completely independant method is presently used by Viera and his coworkers [9] at Los Alamos. In contrast to the method developped at GANIL they use target fragmentation reactions, induced by protons from LAMPF, as a source of neutron-rich nuclei. Their new type of time-of-flight recoil spectrometer called TOFI, allows to extract masses from a high resolution, mass-to-charge determination. The transfer line consists of four electromagnetic quadrupole triplets and a small separated-sector mass-to-charge filter. Many new masses have been measured for neutron-rich light nuclei. In general the masses measured by W. Mittig et al [5] and Viera and al [9] are rather consistent. However for the most exotic isotopes, there is a systematic excess of the second ones over the first ones by about half an MeV. This difference calls for a clarification in the future.

Along an isotopic chain, the increasing number of neutrons appear to result into a decreasing value of the neutron pairing energy [10]. However the persistence of pairing effects at the neutron drip line can be seen from the pattern of particle-stable nuclei. In all the six elements from helium to nitrogen the last stable isotope has even $N(= 2n)$, and the next lighter isotope with $N = 2n - 1$ is, with one exception, unbound. In two cases also the isotope with $N = 2n - 3$ is unbound. This suggests that for a nuclear potential that leaves a single neutron marginally unbound, the additional attractive contribution from the nn interaction will frequently be sufficient to bind two neutrons to the nucleus. The ^{11}Li isotope offers an opportunity where the nuclear structure implications of neutron-neutron interaction could be observed. The mass of ^{11}Li determined by mass spectrometry, corresponds to a binding energy of the last two neutrons to ^{9}Li of 190 ± 110 keV, only. The total interaction cross sections at 790 MeV/u of secondary radioactive fragments were determined by Tanihata et al [11], who used these to calculate the matter radii of the radioactive isotopes. For ^{11}Li they found a remarkably large values (3.27 ± 0.24 fm) and suggested that this might reflect a large deformation and/or a long tail in the matter distribution due to weakly bound nucleons. A recent optical experiment [12] has succeeded in determining the spin value 3/2 for ^{11}Li, and also the magnetic moment ($\mu I = 3.73 \pm 0.13$ n.m) which corresponds to the Schmidt value for a spherical $p_{3/2}$ state. It thus seems plausible that ^{11}Li is a double-closed -shell nucleus with one proton in the p shell. Thus the optical data give no support for the conjecture that it is deformed.

Hansen and Jonson [13] have applied to ^{11}Li considered as a ^{9}Li plus two neutrons the treatment of Migdal [14] for the three-body problem. Indeed Migdal, in the early 70's, conjectured that several nuclei should exhibit a bound state of that type, which he described as a dineutron near the nuclear surface.

The wave function calculated in this way predicts a definite correlation between 2n separation energy and the matter radius of ^{11}Li, as it does for similar light nuclei at the neutron drip line such as ^{6}He or ^{8}He. It is found that the experimental values generally agree with this correlation prediction.

This nuclei at the neutron drip line appears to exhibit a neutronization of the nuclei surface, so that the nucleus is surrounded by a neutral halo, that might extend to several times the nuclear radius in the case of ^{11}Li.

Hansen and Jonson [13] also note that these loosely bound structures have Coulomb stripping cross sections that are roughly inversely proportional to investigate clusters and their separation energy.

Actually, the fragmentation of light neutron-rich nuclei has recently been observed [15]. Reactions such as $^{11}L + C \;\; ^{9}Li + X$, and $^{14}Be + C \;\; ^{12}Be$

+ X were studied at 790 MeV per nucleon. The transverse momentum distribution of the fragments exhibit a superposition of two gaussians. A broad one is consistent with the momentum fluctuation of nucleons in nuclear matter, with a width e.g.of 95 ±12 MeV/c in the case of ^{11}Li. But the narrow peak indicates the existence of nucleons with extremely small momentum fluctuations (of 23 5 MeV/c in the case of ^{11}Li. If the method used for stripping reactions is valid for many- nucleon removal, σ^2 is proportionnal to the average separation energy $< \varepsilon >$ of the removed nucleons. For ^{11}Li, the narrow peak corresponds to $< \varepsilon > = 0.34 \pm 0.16$ MeV which is not inconsistent with the 2n - separation energy of 0.19 ± 0.10 MeV. The broad peak, which corresponds to $< \varepsilon > = 6.0 \pm 1.5$ MeV, is consistent with the normal nucleonic separation energy. Therefore it can be considered that the narrow component is produced through the removal of the weakly bound two last neutrons of ^{11}Li. The small width in momentum can also be correlated to large fluctuations in space coordinates. Therefore, qualitatively, the observed large size and the narrow width in the fragment momentum distribution are consistent with the existence of a long tail in the neutron distribution (neutron halo).

An interesting consequence of the existence of a neutron halo was drawn by Hansen and Jonson [13] , in their model where a dineutron orbits around the ^{9}Li one. They calculate the Coulomb dissociation of loosely bound 2n system according to a soft E1 mode. For a Pb target, their prediction ranges from 1.3 to 5.6b, where this wide range of values shows how sensitive the cross section is to the present uncertainly of the binding energy. The experimental section measured by Tanihata and his coworkers [15] 2.4 ±0.6 b, is consistent with this prediction,. Yet the Z dependence is somewhat weaker than the Z^2 predicted dependence.

Obviously, very precise measurements of neutron binding energies at the drip line are needed, together with other spectroscopic studies, to better characterize the unusual behaviours suggested by the ^{11}Li results.

§3. ß-delayed neutron emission

The importance of ß-delayed emission of several neutrons was shown to be a systematic trend, and quite a sizable decay channel, far from the valley of ß-stability. Indeed the increasing distance of these nuclei of the valley of ß-stability translates into increasing values of Q_{β}, the energy available in their ß-decay which eventually opens up the window for decay into particle-unstable states of the daughter nuclei. The observation of the delayed neutrons from such a decay being coincident with the electrons provides a valuable experimental tool for measuring ß-decay half-lives at very low counting rates. This has been shown for the most neutron-rich Na, Mg, K and Ca isotopes [16] where a total coincidence detection efficiency of 30% was obtained by means of a liquid-scintillator neutron counter. Since these experiments have been performed at an on-line isotope separator, they were limited to alcaline elements and their descendants. This is due to the chemical selectivity of the target/ion source combinaison. Since this restriction is not present for a recoil-type separator, a new experiment has adapted a similar neutron counter to the spectrometer LISE [18] at GANIL .

The isotopes of interest were selected by the spectrometer (Fig.3), and implanted in one of the detectors of the solid-state telescope located at the focal point of the spectrometer. The telescope was surrounded by a plastic scintillator of 3mm thickness which detected the ß particles and

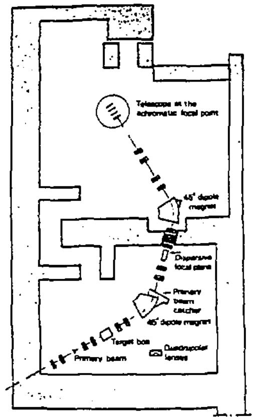

Fig. 3

General layout of the *LISE* spectrometer. Note the two meters concrete shielding between the first and second sections of analysis.

Table 1 Experimental and theoretical neutron emission probabilities

A_X	P_n (%) experimental	P_n (%) theoretical predictions		
		a	b	c
^{17}B	(100)	30	75	75
^{17}C	<11	5.6	15	20
^{18}C	25 ± 4.5	21	51	22
^{19}N	33^{+34}_{-22}	12	29	37
^{20}N	53^{+11}_{-7}	30	77	32
^{34}Al	54 ± 12	9.2	35	20
^{35}Al	87^{+37}_{-35}	26.5	63	44
^{36}Si	<10	3.9	11	6.5
^{37}Si	<15	6.1	20	10
^{38}P	<10	1.4	4.5	7.2
^{39}P	41^{+32}_{-16}	12.4	30	22

a Gross theory [19] with Lorentzian-shaped Gamov-Teller resonance
b Gross theory [19] with Gaussian-shaped Gamov-Teller resonance
c Fitting procedure by Kratz and Hermann [20]

by a fast liquid scintillator NE213 to detect neutrons. This last one was chosen because of its n $-\gamma$ separation properties and for its insensitivity to thermal neutrons.

The technique of correlating the detection of a fragment in the telescope to the detection of a subsequent β - n coincidence allows a measurement of the half-life of the nuclide and of its β-delayed neutron emission probability Pn.

Table 1, taken from ref 18, shows how useful such a study can be far from stability. It confirms the important role of β-delayed neutron processes which must be carefully taken into account in network calculations of nucleosynthesis.

As indicated above, even β-delayed multineutron emission eventually becomes important far from stability. In fact such processes were for long mainly observed for alcaline elements, because of the exceptionally high performance of mass spectrometer ion sources for these elements. Among them ^{11}Li even appeared as an exceptionnal isolated case exhibiting many different β-delayed radioactivities : one, two, three neutrons [21], together with X and ^{6}He, and also the very unusual triton[22] emission. However, the availability of new separation techniques opens the possibility of extending the observation of such rare decay modes for instance to the light elements accessible at GANIL through projectile fragmentation.

A recent study [23] of the β-delayed neutron emission of ^{14}Be, ^{17}B and ^{19}C produced by 60 MeV per nucleon ^{22}Ne

projectiles on a carbon target has revealed new cases of multineutron emission. In that case, the telescope located again at the focal plane of the LISE spectrometer [18], was surrounded by a 4π neutron ball filled with 500 liters of liquid scintillator doped with gadolinium. The contribution of spurious βn coincidences due to the residual background neutrons or to gammas mistaken as neutrons had to be carefully measured. The results are summarized in table 2. Again it shows the importance of such exotic processes. They call for an extension of the theoretical calculations of these processes, as modulator by Lyntostansky et al [24].

One unavoidable question is raised by such a multi particle emission, namely whether the emitted neutrons are energetically and spatially correlated, which might bring new informations on clustering phenomena in nuclei. Although the experimental study of this question is not yet possible, there was a recent suggestion [25] to make use of the 34n emission from ^{17}B to address the ever recurrent problem of multi-neutron nuclei[26].

TABLE 2

	$T_{1/2}$ (ms)	P_{0n}	P_{1n}	P_{2n}	P_{3n}	P_{4n}
^{14}Be	4.35(17)	0.14(3)	0.81(4)	0.05(2)	-	-
^{17}B	5.08(5)	0.21(2)	0.63(1)	0.11(7)	0.035(7)	0.004(3)
^{19}C	49 (4)	0.46(3)	0.47(3)	0.07(3)	-	-

§4. β-Delayed proton emission

The detection of protons present clear technical advantages over the detection of neutrons. So, it might be infered that the general questions discussed above for the decay of neutron-rich nuclei might be more readily studied for neutron-deficient ones. However, the slope of the valley of stability is much steeper on the neutron deficient side so that interesting features when the binding energy lingers about zero, such as the neutron halo, might be absent. Furthermore, this steepness leads to a much smaller number of isotopes. Indeed the proton-drip line has been mapped up to Z = 21, while the neutron drip line is known up to Z = 7 only[7].

It remains that spectrocopic studies with ß-delayed proton emission can be more precise and specific than ß-delayed neutron emission. Many examples of the fruitfulness of that process are described in a recent review of Äystö and Cerny [27].

The prediction that ß-delayed two-proton emission could occur is relatively recent [28]. Odd-odd Tz = − 2 nuclei appeared as the best candidates for this new process and indeed two such nuclei, ^{22}Al and ^{26}P, were shown [29, 30] to emit two protons in coincidence after ß-decay to the T = 2 analog state in the daughter nucleus.

Other emitters could be predicted. For instance the even − Z, Tz = − 5/2 nuclei, in the sd and fp − shells as well, can be expected to feed a strong 2p − branch from their analog states in the Tz = − 3/2 daughter nuclei, as would the few even more neutron-deficient nuclei predicted or observed, as ^{22}Si (ref. 31), to be stable.

The systematic search for these emitters led first to the discovery of ^{37}Ca, precisely through its ß-2p decay channel [32], then to the whole series of the Tz = − 5/2 isotopes [33], ^{23}Si, ^{27}S, ^{31}Ar and again ^{35}Ca, by fragmentation of ^{40}Ca projectiles at GANIL. Precise spectroscopic studies of these nuclei are being conducted. In particular the ß-delayed proton decay of ^{31}Ar, produced this time from an ^{36}Ar projectile, has already been reported [34]. The isobaric analog state in the daughter ^{31}Cl nucleus is expected to decay by both one-and two- proton emission. Yet there is no evidence for any proton yield with the expected energies, 12 and 9.8 MeV for a decay to the ^{30}S ground and first excited states, respectively. On the contrary, there is some evidence that a two-proton decay branch of the IAS into ^{29}P + 2p might be observed. The low production rate of the very exotic ^{31}Ar nucleus, its low ß-branching ratio to the IAS in ^{31}Cl, 5% only, both make this study difficult and call for further investigations. Yet, it already appears that in the ß-decay of ^{31}Ar, as already observed for ^{26}P and ^{22}Al, the branching ratio for two-proton emission from the IAS is certainly comparable to the one-proton emission.

The two-proton emission mechanism, now open to investigation by the results discussed above, is of utmost importance. It directly brings informations on the two-proton correlations inside nuclei. It is quite a unique method since it is free of all the uncertainties inherent to the dynamical treatment of two-proton transfer reactions.

In principle, the two protons can result from several mechanisms, which include decay involving a final state interaction between the two protons (^{2}He emission), uncoupled simultaneous emisssion or sequential emission[35]. In the case of ^{2}He emission, a strong angular correlation at small angles between the emitted protons is expected. A most probable angle of emission of 30° can be deduced from the He breakup energy distribution observed in direct reaction studies, while individual proton spectra should follow a distribution symmetric about $E_1 = E_2$ in the laboratory system with its shape determined by the final state interaction energy ε. In an uncoupled simultaneous emission, where no intermediate states are formed, a continuum of individual proton energies, such as in the case of ^{2}He, is expected. Unlike ^{2}He emission though, a nearly isotropic angular correlation between the protons is expected.

Energy correlation measurements of the ß-delayed protons emitted by ^{22}Al and ^{36}P have clearly established the dominance of a sequantial mechanism[35]. Yet some component of another mechanism, such as ^{2}He emission, cannot be ruled out. It would be of fundamental importance to reach a better knowledge on this point.

The higher yields of ^{22}Al available at GANIL offer a valuable opportunity to restrict the uncertainties of the experiment reported in ref 35. The emission of two protons to form ^{20}Ne (0+) occurs from the 4+, T = 2 state of ^{22}Mg populated with a 2.9% branching ratio by a Fermi β transition from ^{22}Al. Thus it is compatible with the emission of a ^{2}He ($^{1}S_{o}$ state of two protons) carrying a L = 4 angular momentum, while such is not the case for the β-delayed 2p emission of ^{26}P, the other candidate for this study, where the analog state in ^{26}Mg has a 3+ character.

The experiment [36] planned at GANIL to investigate the actual mechanism of 2p emission will make use of an anticiped production rate of ^{22}Al as high as about 15 per second and an elaborate detector where the ^{22}Al will be implanted in a position sensitive detector while the two protons will be recorded by a double strip detector both in the vertical and horizontal detections to define the kinematics of the emission as precisely as needed.

The experimental developments in the detection of β-delayed proton emission now legitimate the search of a new rare decay mode i.e β-delayed three-proton emission. Again ^{31}Ar appears as the best candidate for the time being since an energy of 4.3 MeV is available for the 3p decay of the IAS. A 1% branching ratio for this mode is the predicted sensitivity of this study [36] which will soon be undertaken at GANIL by the Bordeaux group and its coworkers.

§5. New radioactivities

As experiments allow the study of nuclei ever closer of the drip lines, one may expect further variety in the scope of radioactive phenomena already reported (Fig. 4). Among them, the observation of the direct emission of more than one nucleon brings direct information on the correlations and clustering phenomena in nuclei. Once the effect of barrier penetrability is calculated, the emission probability is directly related to the spectroscopic amplitude of the emitted nuclear fragment inside the nucleus. The recently discovered ^{14}C decay mode of ^{223}Ra (Ref. 37) and all the radioactive processes of the same kind reported afterwards have allowed a very fruitful test of the wave functions of the heavier nuclei as well as of the dynamical treatment of barrier penetration [38] .

The two-proton radioactivity, when observed, would bring valuable information on nucleon-nucleon correlations in nuclei. This predicted radioactivity stems from the fact that pairing effects make the binding energy of many even-Z proton-rich nuclei stronger against one-proton than two-proton emission. At the proton drip line it might happen that a nucleus is thus bound for one proton emissison but is able to decay by the emission of two protons. This process was discussed long ago by Goldanskii [39] and Jänecke [40] . The probability of this emission is governed by barrier penetration which itself strongly depends upon the kinematics of the two protons. It is calculated 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 $T_{1/2}(2p)$ 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 $T_{1/2}(2p)$ value is not that much longer than the competing $T_{1/2}(\beta)$ value as to make the 2p branching ratio vanishingly small. Thus a narrow energy window, say − 0.4>

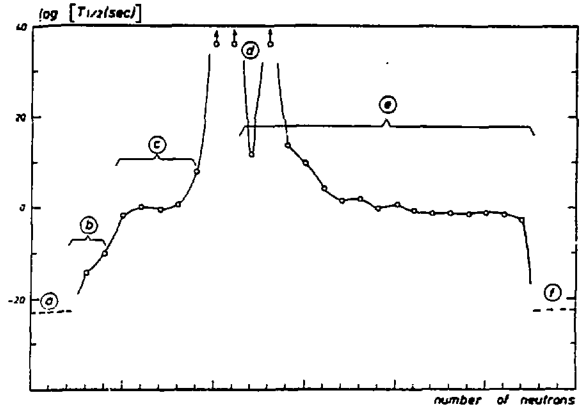

Fig. 4

Typical variation with N, the neutron number, of the radioactive half lives of isotopes of given Z. So-called stable nuclei (region d) have $T_{1/2}$ 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. If the nucleus is bound for hadron emission but can β-decay, $T_{1/2}$ ranges from 1 ms up, the shortest half-life yet observed being 1.5 ms for ^{35}Na. 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. At last if the nucleus is unbound for neutron emission, $T_{1/2}$ falls brutally down to some 10^{-23}s. 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 lowenergy proton. Thus, for available proton energies smaller than about 1 MeV (region b) proton radioactivity can take place and was actually observed. 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 obviosly 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.

E_{2p} >- 0.8 MeV, exists for potential candidates for 2p radioactivity with Z values around 15 or 20.

Two nuclei, which are within reach of GANIL experimental possibilities, are candidates to exhibit the new 2p radioactivity, ^{31}Ar and ^{39}Ti which are predicted to be unbound by 230 keV and 790 keV, respectively. The decay of the first one was observed recently [34]. The half life measured, 15 $\pm$ 3 ms, shows that this decay appears consistent with a usual ß decay, so that 2p emission, if at all present, is very marginal. This is in line with the predicted 230 keV energy available for the two protons, too weak to allow a barrier transmission fast enough to overcome the ß-decay competition. The search for ^{39}Ti is still in progress.

At last it seems that one more ß-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 He in the daughter nucleus be signigicantly 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. This process also would carry direct valuable information on cluster amplitudes in nuclear wave functions.

§6. Conclusions

The study of nuclei far from stability has definitely moved over the last years from the search of punctual more or less spectacular experimental achievements to a systematic investigation of nuclear properties over a much broader field of nuclei than the one on which our models of nuclei have been established.

New radioactive modes, new deformation regions have already been observed.

Among the most promising aspects of this research, some deal with nuclear correlations. For instance, some opportunities appear to study stationnary (i.e. non dynamical) states of nuclear matter at low density, such as in the neutron halo of some very neutron-rich isotopes (e.g. ^{11}Li). Another example is the growing cases of multi-nucleon radioactive emissions (^{14}C and the like, ß2p, hopefully soon 2p, ...) which give direct access to informations free of reaction dynamics on cluster phenomena inside cold nuclei.

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