SOME SYSTEMATIC PROPERTIES OF NUCLEI FAR FROM THE STABILITY LINE

By

H. ABOU-LEILA, P. K. GAORGY* and S. M. DARWISH**

University College for Girls, Ain Shams University, Egypt.

ABSTRACT

The present work describes some of the more recent developments in the study of medium weight and heavy nuclei far from β-stability. A survey of experimental techniques, results on individual nuclear levels and some statistical properties of excited levels populated in high β-decay is presented.

INTRODUCTION

Systematic prperties of nuclei in the rare earth region ($150 < A < 192$) has been studied by several authors [1-4]. Such systematic accumulation of results are rather useful to clarify the properties of of these nuclei. However review articles on nuclei far from the stability line are rather rare. In the last few years, a huge amount of experimental data concerning these nuclei has been published. We found it useful to present a survey of the more recent developments in the study of these nuclei.

EXPERIMENTAL METHODS

Nuclei far from the stability line could be produced mainly by three methods :

1) *Fission* :

Fission process offers a good source of heavy neutron rich nuclei. Study of delayed radiations from fission fragments as well as γ-radiations from primary products [5]) provided us with an extensive data on levels in even-even nuclei.

---

* Higher Institute of Petroleum and Mining, Egypt.

** Physics Department, Faculty of Science, Cairo University, Egypt.

However, such study needs some sort of fast physical and chemical separation of fragmens. In some cases recoil mass spectrometers were used but in most cases nowadays, the on-line isotopic seperators are used [6, 7]).

2) *High energy proton reactions :*

Spallation, fragmentation and fission reactions using proton beams in the Gev range are used to produce a large number of nuclei. As the cross section for producing nuclei very far from the stability line becomes very small, avery sensitive mass separator is usually required. Klapisch [8]) group in Orsay (France) used the on-line mass spectrometer illustrated in figure (1) to separate neutron rich alkali isotopes. In their experiments [9 - 10]), ^{31}Na, ^{32}Na and isotopes of Rb, Cs and Fr were observed.

In 1961, an isotope seperator on line [0, 11]) has been operated in CERN (usually known as ISOLDE project) to study the products from spallation reactions with 600 Mev protons from the synchrocylotron. In this spectrometer a target of molten La at 1100°C is used to produce Cs isotopes. Analogous techniques have been used to produce Rb and Fr isotopes (the 21 millisecond ^{219}Fr isotope has been observed).

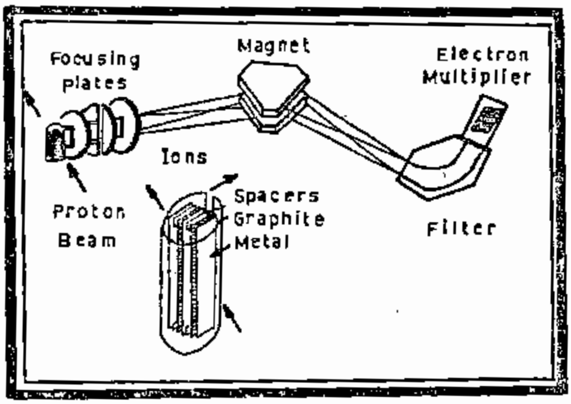

Fig. (1)

The ORSAY on-line mass Spectrmeter

A yield curve illustrating the saturation disintegration rates for Cs isotopes measured at the collector and of the separtor is shown in *Figure 2.*

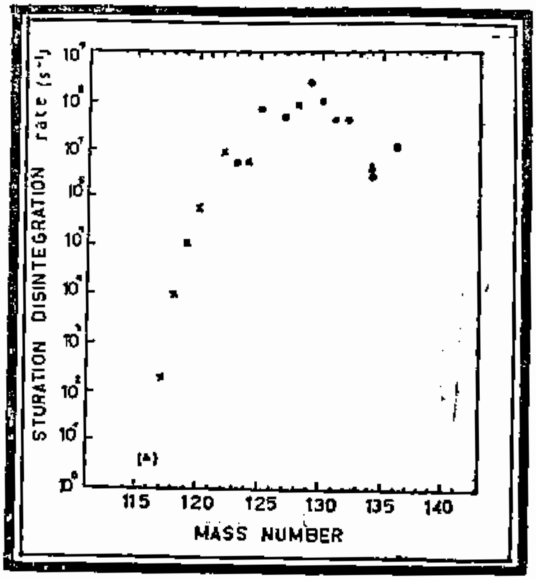

Fig. (2)

Saturation Disentegration rates for Cs isotopes

3) *Heavy ion reactions* :

The cross section for heavy ion reactions shows narrow excitation functions. This narrow excitation function allows the production of few product nuclei at a given energy. In the last few years, an appreciable amount of informations about excited levels in nuclei far from the stability line has been obtained by detecting electrons and γ-rays [12, 13]) following (heavy ion, Xn) reactions. These studies have been useful for elucidating the rotational (and quasi-rotational) bands because of the high angular momentum transferred in such reactions.

It should be noted that the production cross section for very neutron deficient nuclei falls appreciably below the compound nucleus cross section. This is mainly due to the fact that the low proton binding energy leads to a competition between (heavy ion, Xn) and heavy ion, Yn, Zp) reactions. This fact sets a sharp limit [14]) to the production of very neutron deficient nuclei. *Figure (3)* shows part of the chart of nuclei having neutron number $50 < N < 130$ and atomic number $50 < Z < 90$. The dashed line shows the lightest compound nucleus that can be reached by heavy ion reactions.

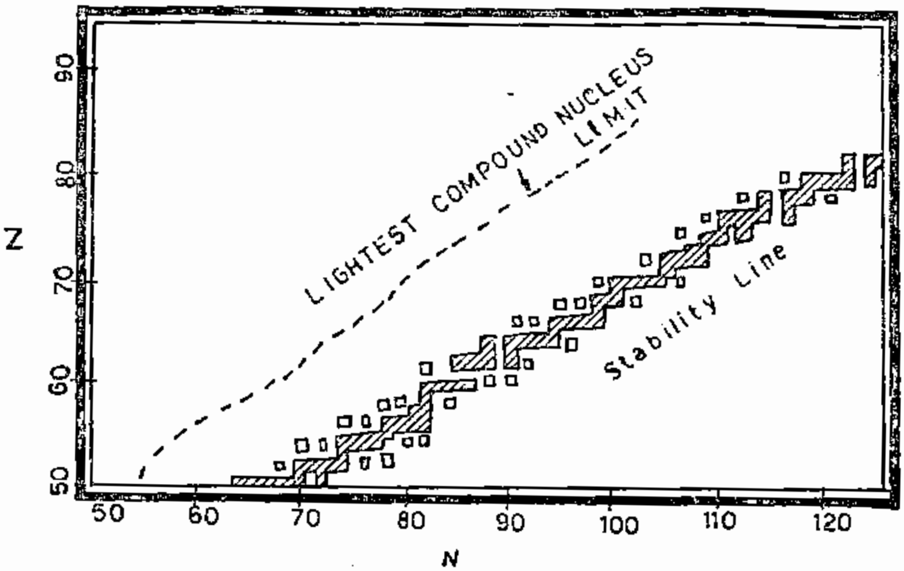

Fig. (3)

Lightest compound nucleus limits for heavy ion reactions

In the region where the cross section of the reaction is very small, it is important to perform measurements far away from he intense radiations emitted from other reactions in the target. If one is interested to identify only the product nucleus, magnetic analysis will be very useful. This method has been used to observe [15]) the formation of ^{30}Mg, ^{42}cl and other nuclides formed in transfer reactions from ^{40} A with ^{232}Th target.

If one is interested to study the delayed radiations from the product nucleus, the helium jet technique (9) is used to transfer the product nucleus very quickly from the target to the detection sytem. In this mehod, the large recoil energy of the product nucleus permits it to escape from the target. There recoil nuclei are slowed down in helium gas and then deposited on a metalic surface by the fast flow of helium through an orifice leading into a region of low pressure.

Properties of ground states and excited levels

1) *Nuclear masses :*

Measurements of the nuclear mass for a given nucleus will give information about its nuclear ground state. Unfortionately, such measurements in the region far from the stability line are very difficult. Direct mass determinations by mass spectroscopy has been used up till now only for relatively light nuclei. Another method is to measure the Q β values in the isobaric decay chains so that one can relate the new masses to known mass values near the stability line. The most complete set of data available up till now for the masses of 182 isobaric chain are given by Westgaard et al (16) in 1971.

2) *Nuclear spins, moments, and excited levels :*

Measurements of spins and moments on-line 9-17) could be done by optical pumping with circularly polarized resonance radiations. Atomic beam magnetic resonance is a very powerful technique for spin and moment determination for off-line experiments. By this method and even with difficult elements, measurements can be made for half-lives down to 2 minutes.

Table 1 shows a selected 18) data from the beautiful series of papers by Gothenburg-Uppsala group. It illustrates the values of systematic measurements of spins for Tm isotopes over a wide mass range. It should be noted that the intensities expected for the improved ISOLDE facilities will be high enough to permit on line atomic beam magnetic resonance measurements.

For systematics of excited levels, a great progress has been made during the past years partly by using on-beam spectroscopy or by studying excited level populated in α and β-decay and in isomeric transition. *Fig (4)* shows some systematics of known levels in neutron deficient Pb isotopes produced by heavy ion reactions 19).

3) *Alpha and proton radioactivity :*

α-emitter nuclei far from the stability line has been studied by several techniques. The helium jet technique has been used to study systematically the α-energies and half-lives in the uranium region (20 - 23) and for osmium isotopes. A similar study (24 - 27) has been done above the N = 82 closed shell in the rare earth region. On line isotopic seperation technique has been used also to study the α-decay of mercury and radon isotopes together with their daughters. *Figure (5)* shows a very interesting α-emitter amoung the light tellurium isotopes. (28)

For extermely neutron-deficient nuclei, the proton binding energies are expected to becomes negative and barrier penetration will then give rise to coulomb-delayed proton emission. However this has not been confirmed. Only weak indications that soft protons are produced with ^{32}S or ^{35}Cl ions on rare earths isotopes have been reported (9, 24, 25).

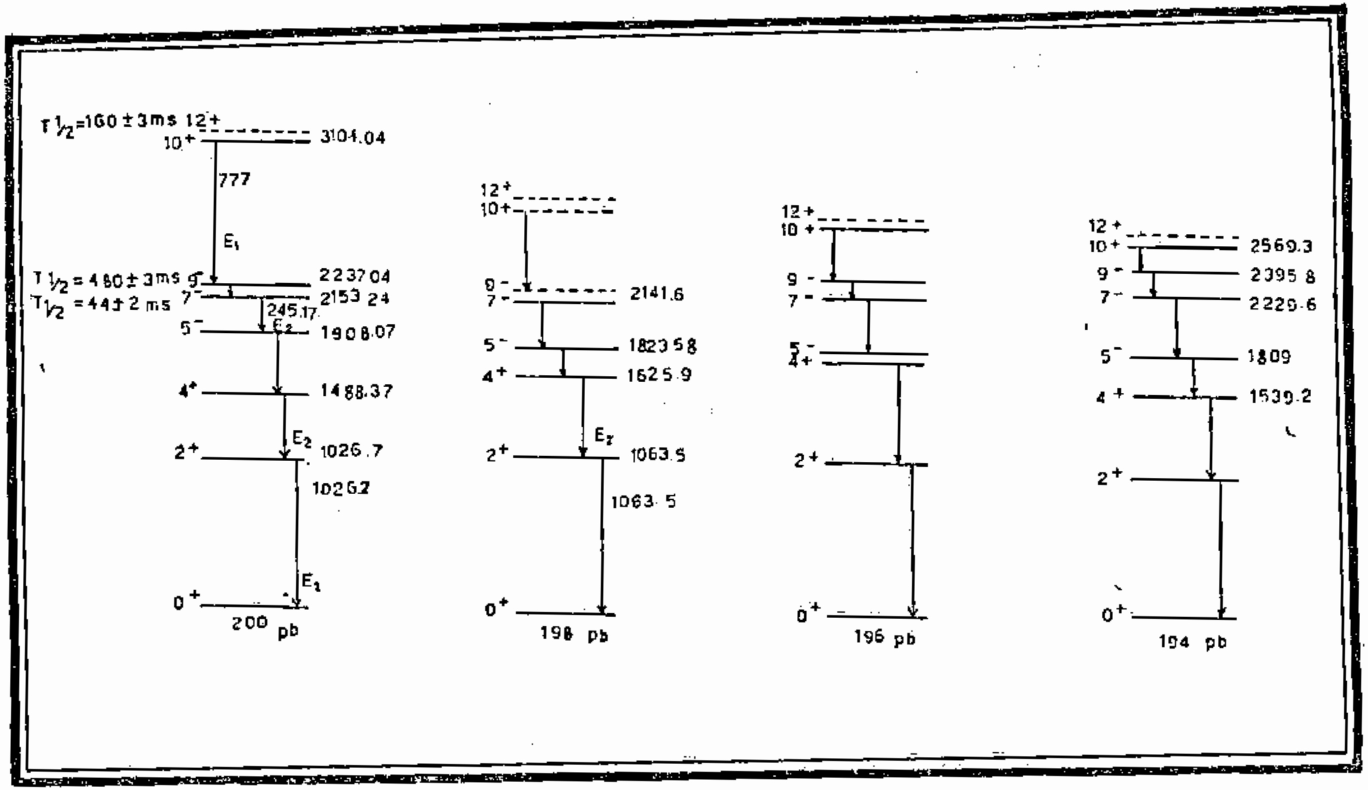

Fig. (4)

Energy levels of Pb isotopes
from on-beam experiments

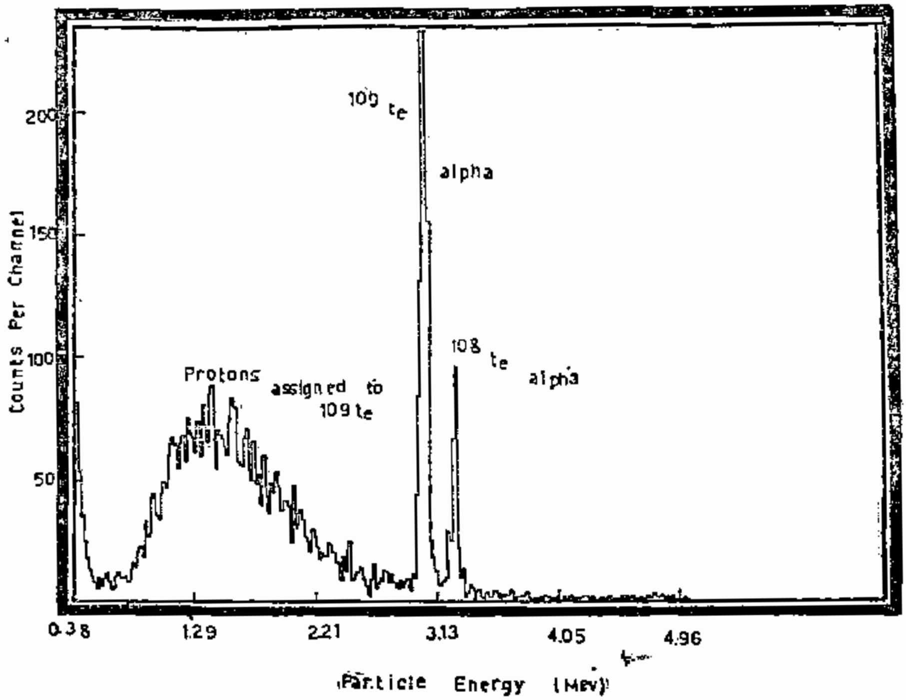

Fig. (5)

Tellurium alpha activities from Ref. 28

The Beta strength function

It is possible to describe how the amplitude for a given reaction channel distributes itself over a large number of levels of a system by the strength function. From the experimental point of view, a strength is expressed as the product of the average reduced width and the level density, for β-decay, the strength function is defined (29) as

$$S_\beta(E) \equiv \frac{b\ (E)}{[\ f\ (Z,\ Q - E\ ).\ T^1\!/\!_2\ ]} \qquad S^{-1}.\ Mev^{-1}$$

Where : b (E) = Absolute β intensity/Mev. of final levels at the energy E in the daughter nucleus.

f = Statistical rate function.

Q = Total energy available for the β decay with half-life T½.

From the theoritical point of view, the β - strength function could be expressed in terms of the average reduced β - transition probability

B_i (E) to levels having energy E, spin and parity I_i^{π} and with density p_i (E) as follows (38)

$$S_{\beta}(E) = D^{-1} \Sigma_i \, p_i(E) \, \overline{B}_i(E)$$

D is a constant (30) = 6260 ± 60 S.

Detailed information about β - strength function could be obtained from the decay scheme for low and intermediate Q-values. For high Q-values, the decay schemes are very complex and one should use good resolution techniques such as total absorption of γ - rays in well (4 π)sodium iodide Thalium activated crystals (29). By this technique, the energy of the compound level populated in the β-decay could be measured by summing the γ - rays emitted in cascade. It was possible to have the following main conclusions :

a) There is a cut-off in the β - strength function for odd-mass and odd-odd nuclei.

b) The β - strength function shows no pronounced energy dependence above the cut-off. Its average values varies systematically with the proton and neutron numbers.

c) The β - strength function shows low energy peaks.

For electron capture decays, it has been possible to measure the β - strength functions down to the light iodine isotopes by adding a 4π positron counter to veto positron decays. *Figure (6)* shows the measured (31) β - strength function for some Xe isotopes. The histogram shows the theoritical values calculated by Martinsan (32) et al. Their calculated values shows :

a) That the neglect of particle hole correlation leads to an over estimation of the calculated β - strength function by a factor of 10.

b) That the main source of β - strenthgth in this region is the

$\left(g^{p}_{9/2}\right)^{-1}\left(g^{n}_{7/2}\right)$ excitation.

An improved experimental technique has been constructed (7) in studsvik in which the γ - cascade were detected in coincidence with β - particles escaping from the γ - counter. It has been shown that in contradistinction to the β^{+}, electron capture strength function the β^{-} strength function shows a very strong increase with energy,

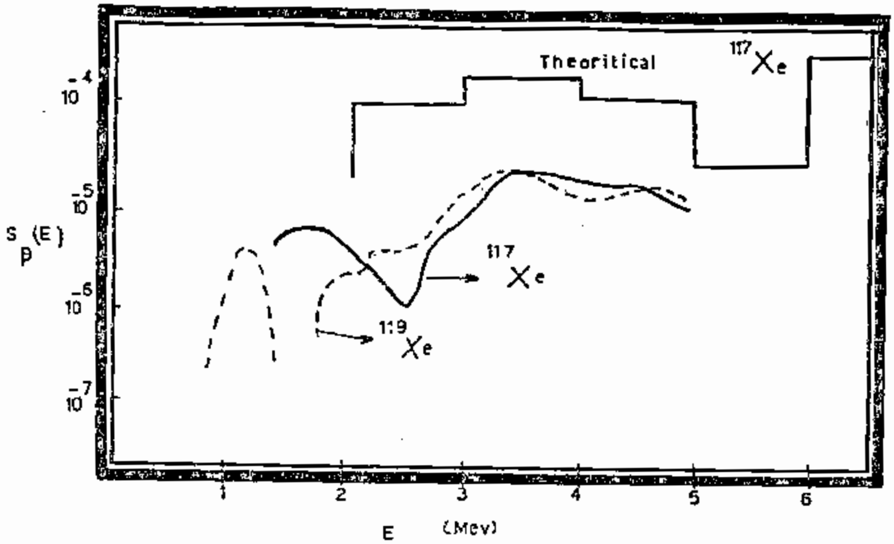

Fig. (6)
β strength functions (31) for (117, 119) Xe
compared with theoritical calculation (32)

It should be noted that the study of fast β - transitions has permitted identification of some complex structure states. In rare earth isotopes for example, a number of three quasi particle levels has been identified (33) through the allowed unhindered transitions of the type

$^5/_2$- (523) $\xrightarrow{\beta}$ $^7/_2$- (523).

Another example is the fast $g^{n}_{9/2} \longrightarrow h^{p}_{9/2}$ and $p^{n}_{1/2} - S^{p}_{1/2}$

transitions (34) in (208) Pb. However one (29) could convert β - half-lives to an average strength $\overline{S}_\beta$ above the cut-off energy C as follows

$$\overline{S}_\beta = (1 - b) \left[T_{1/2} \int_C^Q f(Q - E.Z)\, dE \right]^{-1}$$

where b is the branching ratio for other decay modes competing with β decay. It should be noted that the average β - strength functions calculated from this eqtation agree very well with the more precise values obtained from γ cascade absorption methods.

Another example (29) of the average β - strength function which shows the systematic behaviour with Z and N are shown in figure 7. The smooth behaviour with Z and N provides further evidence that core excitations dominate the β - strength function.

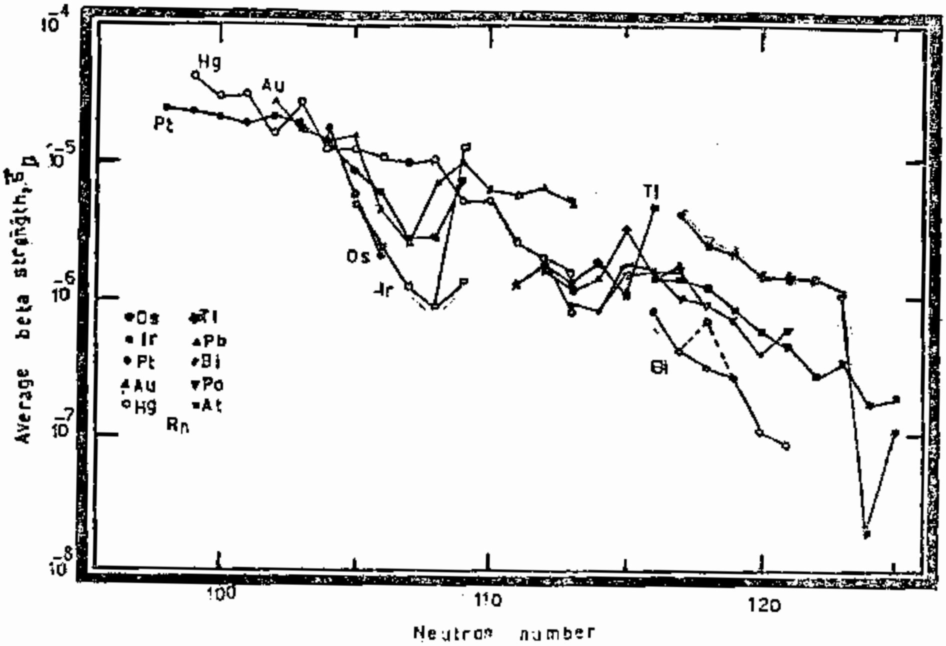

Fig. (7)

Average β_s for neutron deficient isotope in the region Os-Rn

However, the results shows a strong decrease of the β - strength function as the 126th neutron closed shell is approached.

Calculations of average strength function for β- emitters have been done by Damkjaer et al (9). It was found that a strong shell effects at N = 50 and 82 occurs. However the recent observations that the β - strength function depends strongly on energy makes the use of a model constant strength somewhat doubtful.

Conclusion Remarks :

It would probably be interesting to have a systematic survey of decay schemes with high Q - values in order to have more informations about the β - strength function. In fact, much of experimental work is needed to identify a significant amount of transitions either not placed in the decay schemes as remained unobserved. Unfortunately, no high resolution method exists for the time being for probing directly into the β - strength functions at high energy exications.

However, for lower energy levels, a model with simple wave functions form a conventient starting point, but as the work is extended to higher excitation energies, it is to be expected that statistical features will be observable. In fact, nuclei far from the stability line could be considered as exotic nuclei, studying their structure will lead to some surprises. These surprises will provide us with a new experimental toal for learning about the nucleus.

TABLE 1

Nuclear Spins of thalium isotope

A	T ½	I
159	11 min	5/2
160	9 min	1
161	34 min	7/2
162	21 min	1
163	1.8 h	½
164	2 min	1
164^m	5 min	6
165	30.1 h	½
166	7.7 d	2
167	9.6 d	½
168	87 d	3

REFERENCES

1. A. Schwarzchild, Phys. Rev. 141 (1966) 1206.
2. H.W. Kugel, E.G. Funk and J.W. Mihelich, Phys. Rev. 165 (1968) 1352.
3. H. Abou-Leila, Ann. Phys 2 (1967) 181.
4. H. Abou-Leila, A. Abd El Haleim and S.M. Darwish, Nucl Phys. A 175 (1971) 663.
5. E. Cheifetz, R.C. Jared, S.G. Thompson and J.B. Wilhelmy Phys. Rev. Letters 28 (1970) 38.
6. Proc. Int. Conf. on Electromagnetic isotope separations and techniques of their application, Marburg, 1970. (eds. H. Wagner and W. Walcher) BMBW-FB K 70—28 (1970).

7. S. Brg, I. Bergström, G.B. Holm, B. Rhydberg, L.E. de Geer, G. Rudstom, B. Graspengiesser, E. Lund and L. Westgoard, Nucl. Inst. and meth. 91 (1971) 109.

8. R. Klapisch, C. Thibault - Phillippe, C. Detraz, J. Chaumont, R. Bernas and E. Beck., Phys. Rev. letters 23 (1969) 652.

9. Proc. Int. conf. on the properties of nuclei far from the region of β - stability, Leysin, 1970, CERN 70 - 30 (1970).

10. J. Chaumont, E. Roeckl, Y. Nir-El, C. Thibault-Phillippe, R. Klapisch and R. Bernas, Phys. Letters 29 B (1969) 652.

11. The ISOLD Sep. on line fucility at CERN (eds. A. Kjelberg and R. Rudstam) CERN yellow report 70—3—1970.

12. G. Alboug, J. M. Lagrange, M. Pautrat, J.N. Riombert, C. Roulet, H. Sergolle, J. Vanhorevbeeck and H. Abou-Leila, J. Phys. 33 (1972) 835.

13. M. Pautrat, G. Albouy, J.M. Lagrange, N. Proffé, C. Roulet, H. Sergalle, J. Vanharevbeeck and H. Abou-Leila, Nucl. Phys. A 201 (1973) 449.

14. F.S. Stephens, J.R. Leigh and R.M. Diamond, Nucl. Phys. A 170 (1971) 335.

15. A.G. Artukh, V.V. Avdeichikov, G. F. Gridenev, V. L. Mikhneev, V.V. Volkov and J. Wilczynski, Nucl. Phys. A 176 (1971) 284.

16. L. Westgaard, J. Zylics and O.B. Nielsen, Proc. 4th Int. Conf. on Atomic Masses and fundamental constants, NPS, Teddington (1971).

17. J. Bonn, G. Huber, H. J. Kluge, U. Köpf, L. Kugler and E. W. Otten. Phys. letters 36 B (1971) 41.

18. G. Ekström, M. Olsmats and B. Wannberg, Nucl. Phys. A 170 (1971) 649.

19. M. Pautrat, Thèse de Doctoratés - sciences ORSAY (FRANCE) serie A, NO. d'ordre 928, 1972.

20. K. Valli, E. K. Hyde and J. Brggren, Phys. Rev. Cl, (1970) 2115.

22. J. Brggren, K. Valli and E. K. Hyde, Phys. Rev. C2 (1970) 1841.

23. J. Brggren and E. K. Hyde, Nuclear Phys A 162 (1971) 407.

24. R.D. Mac farlane, Phys. Rev. 136 (1964) B 941.

25. R. D. Mac farlane, Phys. Rev. 137 (1965) B 1448.

26. K. S. Toth and R. L. Habn, Phys. Rev. C3 (1971) 854.

27. K. S. Toth, R. L. Habn and M. A. Ijaz, Phys. Rev. C4 (1971) 223.

28. R. D. Macfarlane, Arkiv for Fysik 36 (1967) 431.

29. C. L. Duke, P. G. Hansen ; O. B. Nielsen and G. Rudstam, Nucl. Phys. A151 (1970) 609.

30. A. Bohr and B. R. Mottelson, Nuclear structure (Benjamin Inc., New York, 1969).

31. P. Hornshj, K. Wilsky, B. Erdal, P. G. Hansen, B. Jonson, K. Johansson and G. Nymen, to be published.

32. Martinsen and J. Randrup, to be published.

33. M.E. Bunker and C. W. Reich, Rev. Mod. Phys. 43 (1971) 348.

34. R. K. Gupta and K. S. R. Sastry, to be published.