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PRODUCTION AND IDENTIFICATION OF VERY EXOTIC NUCLEI

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I would like to dedicate this work to our gifted colleague and friend Michel LANGEVIN deceased on 11 April 1985. He promoted the use of the spectrometer LISE and he initiated all these fruitful experiments.

The experiments described in this paper have been performed by the following physicists :

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I - INTRODUCTION

Recent studies on exotic light nuclei have provided critical information on the limits of nuclear stability, on nuclear shapes and on the occurence of new decay modes. Establishing the limits of particle stability for nuclei has been the goal of many experiments for many years 1).

With regard to the neutron rich side of the chart of nuclides (fig. 1), the search for new neutron rich isotopes has much benefitted from the effectiveness of heavy ion projectile fragmentation at relativistic 2) 3) 4) 5) or, more recently, at intermediate energy 6) 7). But even if the experiments demonstrating the existence or not of nuclei are for more advanced than those giving decay modes or accurate masses, the neutron drip line has, so far, been reached up to boron ($Z = 5$).

With regard to the proton rich side, the limit of nuclear stability against one and two proton emission has been intensively investigated in the recent past (ref. 8, 9). In particular several experiments to study $T_z = -2$ nuclei individually have been reported. These experiments identify nuclei through their radioactive decay mode, β delayed proton emission in the case of ^{32}Ar (ref. 10) and the new mode of β-delayed two-proton emission from ^{22}Al and ^{26}P (ref. 11). A very recent report of the first observation of a $T_z = -5/_2$ nucleus (^{35}Ca) is based on such a β delayed two-proton activity 12). Most updated mass formulae 13) 14) 15) predict that the four $T_z = -5/_2$ nuclei ^{23}Si, ^{27}S, ^{31}Ar and ^{35}Ca are stable or nearly stable against proton emission. However these nuclei have not been directly observed yet.

Therefore a far better knowledge of the drip line is a fundamental step in our understanding for the following reasons. It is the most extreme condition imposed on an unexcited nucleus which provides a demanding test for nuclear theory and the search for nuclei near the drip lines attacks a frontier where new phenomena such as decay modes are to be observed.

The new accelerator facility GANIL at CAEN is devoted to heavy ion physics in the intermediate energy range 20-100 MeV/u. High intensity beams with excellent focal qualities are available at the target positions. Since two years, reaction mechanism studies, have shown that a large part of the reaction mechanism gives rise to the production of projectile like fragments with a narrow dispersion in energy and angle around 0° (ref. 16). The effectiveness of heavy-ion fragmentation at relativistic energies for producing neutron rich nuclei has been proved (ref. 2, 3, 4, 5). Although the energy dispersion is larger than the one used at higher energies to observe exotic nuclei, the intensities available at GANIL (10^{12} pps for light ions and a few 10^{10} pps for Kr) obviously make this accelerator the ideal tool for producing exotic nuclei through projectile fragmentation.

The work undertaken by our group using the new accelerator GANIL is presented as follows :

- the experimental set-up is described in section 2
- data on production and identification of new neutron rich nuclei are shown in section 3
- section 4 deals with new results obtained on the proton drip line up to $Z = 20$
- finally short-dated and long-dated prospects are discussed.

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II - EXPERIMENTAL SET-UP

The LISE spectrometer installed at GANIL is a double achromatic system consisting essentially of two identical dipoles set at 0° (fig. 2). The first one is used as a dispersive element, the second one allows the compensation of the dispersion of the first element. The dispersive focal plane may be equiped with a slit, a stripper or an energy degrader depending on the experiment.

With such a system it is possible to get at the achromatic focal point a double achromatism both in angle and in position. The maximum rigidity analysis is 3.2 Tm, the central trajectory radius 2m, the maximum angular acceptance 1m sr and the maximum acceptance $\frac{\Delta B\rho}{B\rho} = \pm 2.5\ \%$.

(For more details on the spectrometer see ref. 17).

The detection system consists of two ΔE Si surface barrier detectors, a thick SiLi E detector and a veto one. The time of flight of the detected fragments on the 18 meters long well defined path from the target to the detectors, is measured by deriving a start signal from the time signal of either of the ΔE detectors and a stop signal from the radio frequency (RF) signal of the last cyclotron. The time resolution obtained in these experiments is 1 % of the typical flight time of about 200 ns through LISE.

The atomic number Z of the detected fragments is basically determined by the energy loss in the first and second detectors and the time of flight through LISE. The Z identification is excellent ($\frac{\Delta Z}{Z} =$ 1 %) without any overlap between adjacent elements (fig. 3).

The A identification was obtained up to very recently with the total energy and the time of flight. The mass resolution was good $\frac{\Delta A}{A} \sim 1.5\ \%$ but did not give a good mass separation for A>50. Very recently (nov. 85) a parallel plate avalanche counter (PPAC) has been set in the focal plane of the first dipole and gives a very good position i.e. a very good Bρ determination which gives rise to an excellent A resolution $\frac{\Delta A}{A} < 0.5\ \%$.

These double Z and now double A identifications ensure a very low background and an unambiguous fragment identification.

The optimum setting of the LISE spectrometer for a given reaction fragment (Z,A) relies on the reaction mechanism which defines its most probable energy and on the energy loss effects in the target.

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III - PRODUCTION AND IDENTIFICATION OF NEW NEUTRON RICH NUCLEI

A) LIGHT NEUTRON RICH NUCLEI AND THE REACHING OF THE NEUTRON DRIF LINE.

The goal of these experiments was to produce new light neutron rich nuclei $4 < Z < 10$ at the limit of the stability. The kinematic properties of projectile fragmentation mechanism : fragments emitted around 0° at velocities close to the one for the incident beam, allow for magnetic separation. This feature, essential for the suppression of high counting rates due to the primary beam is a necessary condition for the identification of new isotopes at the borders of nuclear stability where extremely low production cross sections are to be expected. Two years ago the neutron drip line was only reached up to Beryllium ($Z = 4$).

Two experiments have been performed within this aim (May 84 and July 85). The ^{40}Ar (44 MeV/u) GANIL beam, now available at a mean intensity of 3×10^{11} particles/second, has been used to bombard a 85 mg cm^{-2} tantalum target (166 mg cm^{-2} in the second experiment).

A sample of mass spectra obtained in the first experiment[6)] is shown on fig. 4. The results are the following :

- First observation and thus existence of ^{23}N, ^{29}Ne and ^{30}Ne
- Non observation of ^{18}B, ^{21}C and ^{25}O

The existence of ^{23}N and ^{30}Ne and the particle unstability of ^{18}B, ^{21}C and ^{25}O are predicted by most recent mass calculations (ref. 13, 14, 15) but ^{29}Ne is in the same way predicted to be particle unstable with the exception of the UNO and YAMADA constant shell term formula (ref. 13). This model gives a general trend for increasing of particle stability in the $Z = 10$ neighbourhood. Even A neon isotopes are predicted particle stable up to ^{38}Ne and this tendency can be reinforced by the onset of a new deformation area at the vicinity of $N = 20$ (ref. 18).

Concerning the reaching of the neutron drip line it is clear that this first experiment was a good step towards the drip line but the ^{22}C, the ^{26}O and the ^{32}Na had still to be searched for.

The aim of the second experiment was indeed to search for these extremely exotic nuclei. Two settings of the spectrometer ($B\rho = 3.10$ Tm and $B\rho = 3.20$ Tm) were used to search for the ^{22}C and ^{19}B isotopes. The total exposure time was of about 30 hours with an ^{40}Ar beam of 3×10^{11} particles/second on a 166 mg cm^{-2} tantalum target. The mass distributions for the B and C isotopes are shown on fig. 5. Since they have been obtained by summing up different magnetic rigidity the observed yields are a convolution of several effects and do not reflect the primary production cross sections. For the first time, the extremely exotic ($T_z = +5$) nucleus ^{22}C is observed. The non stability of ^{21}C is confirmed. The odd even effect at the limits of nuclear stability predicted by the mass formulae is nicely seen for the carbon isotopes.

The recent observation of ^{19}B 5) is confirmed at a level of much higher statistics. Still 112 counts of ^{19}B but none of ^{20}B have been observed and adopting the criterion of a monotonically dropping yield between the A and A + 1 isotopes the non stability of ^{20}B is claimed.

In this same experiment the ^{23}N stability is also confirmed with a higher level statistics (130 counts) and no counts of ^{24}N is observed giving evidence of the particle unstable character of ^{24}N.

The predicted one and two neutron binding energies (Sn, S_{2n}) for B, C and N isotopes according to the formulae of (a) J. Janëcke 15) and (b) Uno and Yamada 13) are shown on fig. 6. It is seen from these curves that the last predicted bound isotopes are respectively the ^{19}B, the ^{22}C and the ^{23}N.

So, in our last experiment the neutron drip line has been reached, experimentally up to nitrogen isotopes (Z = 7).

During the same experiment the LISE spectrometer was tuned to observe the predicted bound isotopes ^{26}O, ^{29}F and ^{32}Ne. About 30 hours of integrated beam with three different Bρ exposures were spent but no counts attributed to these isotopes were found. It can be though that this lack of events is due to a problem of reaction mechanism.

B) MEDIUM NEUTRON RICH NUCLEI

So far, the most neutron rich nuclei in this region ($18 < Z < 27$) were produced by either deep inelastic 19) 20) or multinucleon transfer reactions 21) 22). In this work the exotic nuclei were produced by the fragmentation of 33 MeV/u ^{86}Kr projectiles. 63 mg/cm^2 thick titanium and 83 mg/cm^2 thick tantalum targets were bombarded by $2.5 \, 10^{10}$ pps.

The mass spectra obtained in a five hours run are shown in fig. 7. As already demonstrated in our first experiment, an advantage of this experimental method is a negligible background. The A resolution ensures clearly separated peaks for masses $A < 50$. A check of the mass calculated by the time of flight was performed with the known nuclei in the range $Z = 8$ to $Z = 20$ and the precision of, the calibration was found to be 0.1 mass unit. Therefore there is no ambiguity in the mass assignment even at low statistics. Results are the following :

- The tentative observation of the new isotopes ^{56}Ti, ^{57,58}V, ^{60}Cr [20] and ^{65}Fe [19] is confirmed.

- Three nuclei produced recently by multinucleon transfer reactions at GSI [21] are also observed. They are namely ^{63}Mn, ^{66}Co, ^{67}Co.

- In addition to that are identified for the first time, the following forteen new isotopes : ^{47}Ar, ^{57}Ti, ^{59,60}V, ^{61,62}Cr, ^{64,65}Mn, ^{66,67,68}Fe, ^{68,69,70}Co.

- There are also hints for the observation of ^{54}Sc and ^{66}Mn.

All these new nuclei are predicted to be particle stable and they are quite far from the neutron drip line ! From this point of vue the synthesis of all these nuclei is not so important than the one of the first experiment.

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IV - MAPPING OF THE PROTON DRIP LINE UP TO Z = 20

The effectiveness of intermediate energy heavy-ion fragmentation in the production of neutron rich nuclei far from stability suggests the extension of our experimental technique to a search for very proton-rich light nuclei.

In the past few years several experiments, which identify nuclei through their radioactive decay mode, to study Tz = -2 nuclei have been reported (ref. 8, 10, 11). Most updated mass formulae (ref. 13, 14, 15) predict that the four Tz = -5/2 nuclei ^{23}Si, ^{27}S, ^{31}Ar and ^{35}Ca are stable or nearly stable against direct two proton emission. A very recent report of the first observation of a Tz = -5/2 nucleus, ^{35}Ca is based on a β delayed two proton activity (ref. 23).

Our search for the Tz = -5/2 series used the fragmentation of a 77 MeV/u ^{40}Ca beam on a 92 mg/cm^2 natural nickel target 25).
The incident energy was chosen to approach, within the characteristics of GANIL24) the relativistic regime for which the fragment velocities are close to the incident beam velocity. Proton-rich nuclei were chosen for both the projectile and target to enhance the production rate of proton rich nuclei. Such a choice is known16) to be effective at intermediate energy.

The bidimensional plot of time of flights (TOF), proportional to A/Z, versus Z is shown on fig. 8. This plot exhibits characteristic curves which are labelled by their isospin projection Tz. The line of constant TOF corresponds to A/Z = 2, Tz = 0, N = Z self conjugate nuclei, located in the stability valley. The presence or absence of well known isotopes in these Z lines is clear ly observed : the absence of ^{8}Be (Tz = 0), ^{9}B (Tz = -1/2) and ^{16}F (Tz = -1) correlated with the presence of ^{9}Be (Tz = 1/2), ^{8}B (Tz = -1) and ^{10}B (Tz = 0) assures the Z calibration.

Figure 9 is the same bidimensional representation but centered on the proton rich nuclei after 14 hours of integrated beam. The Tz = -5/2 series, namely ^{23}Si, ^{27}S, ^{31}Ar and ^{35}Ca is greatly observed.

The question of wether the proton drip line has been reached up to Z = 20 by the present experiment should be handled with some precaution since the steepness of the valley of β stability on this side does preclude any definite statement as the non observation of a given isotope. Nevertheless, all nuclei Tz = -2, Tz = -5/2 and Tz = -3 non observed in this experiment, are predicted to be unbound against one or two proton emission.

The 1 and 2p separation energies have been calculated [25] by applying the charge-symmetry formula of Kelson and Garvey as done by Janecke [15] but using the most recent experimental masses [27] for the conjugate neutron rich nuclei. The only possible exception would be the ^{22}Si predicted to be bound against 2p emission by 16 ± 300 keV.

The present study certainly marks an important and may be definitive step towards mapping the proton drip line for light nuclei ($Z \leq 20$).

The figure 10 gives a summary of all the new nuclei observed in these experiments.

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IV - PROSPECTS

Concerning short-dated prospects, the fragmentation of a ^{58}Ni beam, now available at GANIL, should allow an extension of our experiment for producing proton rich nuclei to still higher Z values i.e. possibly up to Z = 28.

But, since the information that we learn in such experiments is limited (stability or not), they are only a first step in the study of exotic nuclei. The next step is to determine the fundamental constants of these nuclei i.e. nuclear masses, half-lives and decay modes. The observed production rates of exotic nuclei should permit further study of their β delayed proton or neutron-emission.

In the LISE spectrometer, by putting a thick energy degrader in the first focal plane and by tuning the second dipole on some selected nuclei, only four or five nuclei, with very different half lives, are focussed in the telescope (see fig. 11). The protons will be detected in the same telescope than the exotic nuclei with very thin solid state detections. The neutrons will be detected in a special neutron detector set around the telescope.

An exciting goal of the next experiments will be the search for the new two proton radioactivity. The observation of ^{31}Ar, predicted to be 2p unbound by 180 keV may point to a contingent case of this direct two proton emission. The possibility of such a decay from nuclei bound to 1p but slightly unbound to 2p emission was discussed long ago by Goldansky$^{28)}$ and later on by Jänecke$^{29)}$ Different considerations $^{25)}$ lead to the conclusion that this 2p radioactivity can be observed in our experiment if the proton energy is in the narrow window 500 keV < Epp < 800 keV. The observation of ^{31}Ar in our experiment only confirms that this nucleus is not unbound by more than 800 keV. The ^{39}Ti, if observed in our experiment, would be a better candidate for this 2p radioactivity.

In conclusion, this physic of "exotic nuclei" is a large open field with a future and the improved GANIL facility (1987-88), the new "SIS - ESR" project at DARMSTADT (1990) guarantee the ability and the interest for experiments in that field.

REFERENCES

1) See for example :

- The 7th Int. Conf. on Atomic Masses and Fundamental Constants (AMCO. 7) Darmstadt, Sept.84.
- The 4th Conf. on Nuclei far from Stability, Helsingør, June 81.

2) T.J.M. Symons et al., Phys. Rev. Lett. 42 (1979) 40.

3) G.D. Westfall et al., Phys. Rev. Lett. 43 (1979) 1859.

4) J.D. Stevenson and J.P. Price, Phys. Rev. C24 (1981) 2101.

5) J.A. Musser and J.D. Stevenson, Phys. Rev. Lett. 53 (1984) 2544.

6) M. Langevin et al., Phys. Lett. 150B (1985) 71.

7) D. Guillemaud-Mueller et al., Z. für Physik A322 (1985) 415

8) M.D. Cable et al., Phys. Lett. 123B (1983) 25.

9) J. Aysto and Jo Cerny, Future directions in studies of nuclei far from stability.
J.H. Hamilton et al., North Holland, Amsterdam (1980) p.257.

10) T. Björnstad et al., Nucl. Phys. A443 (1985) 283.

11) M.D. Cable et al., Phys. Rev. C30 (1984) 1276

12) J. Aysto et al., Phys. Rev. Lett. 55 (1985) 1384.

13) M. Uno and M. Yamada, INS Report NUMA 40 (1982) and Prog. Theor. Phys. 65 (1981) 1322.

14) P. Möller and J.R. Nix, At. Data Tables 26 (1981) 165.

15) S. Maripuu and J. Janëcke, at Data and Data Tables 17 (1976) - Special editio

16) D. Guerreau, invited talk to the nucleus-nucleus collisions II
Visby (1985). Preprint GANIL P 85-09 and references cited therein.

17) R. Anne and C. Signarbieux, GANIL report RA/NJ 278 (1982)
M. Langevin and R. Anne, GANIL report P. 84-16 and
Proceedings Conf. on Instrumentation for Heavy Ion Nuclear Research,
Oak Ridge, Oct. 22-24 (1984)

18) E. Quiniou, Thesis Orsay (1985) IPNO T 85-02
H. Flocard, Private communication
P. Bonche et al., IPNO TH 85-12, Nucl. Phys. A443 (1985) 39.

19) D. Guerreau et al., Z. Phys. A295 (1980) 105

20) H. Breuer et al., Phys. Rev. C22 (1980) 2454

21) E. Runte et al., Nucl. Phys. A399 (1983) 163
E. Runte et al., Nucl. Phys. A441 (1985) 237

22) R.T. Kouzes et al., Nucl. Phys. A307 (1978) 71

23) J. Aysto et al, Phys. Rev. Lett.55 (1985) 1384

24) A. Joubert in Proceedings of the Xth Int. Conf. on Cyclotrons and
their applications East Lansing (1984) ed. F. Marti(IEEE New York
1984) p.3

25) M. Langevin et al. - Submitted to Nuclear Physics -
Preprint GANIL 85-16.

26) I. Kelson and G.T. Garvey, Phys. Lett. 23 (1966) 689

27) A.H. Wapstra and G. Audi, Nucl. Phys. A432 (1985) 1.

28) V.I. Goldansky, Nucl. Phys. 19 (1960) 482
Nucl. Phys. 27 (1961) 648
La Recherche (Nov.1972)

29) J. Janëcke, Nucl. Phys. 61 (1965) 326

30) J.C. Hardy, Exotic Nuclei and their decay,Science vol.227
(1 march 1985) p.4690.

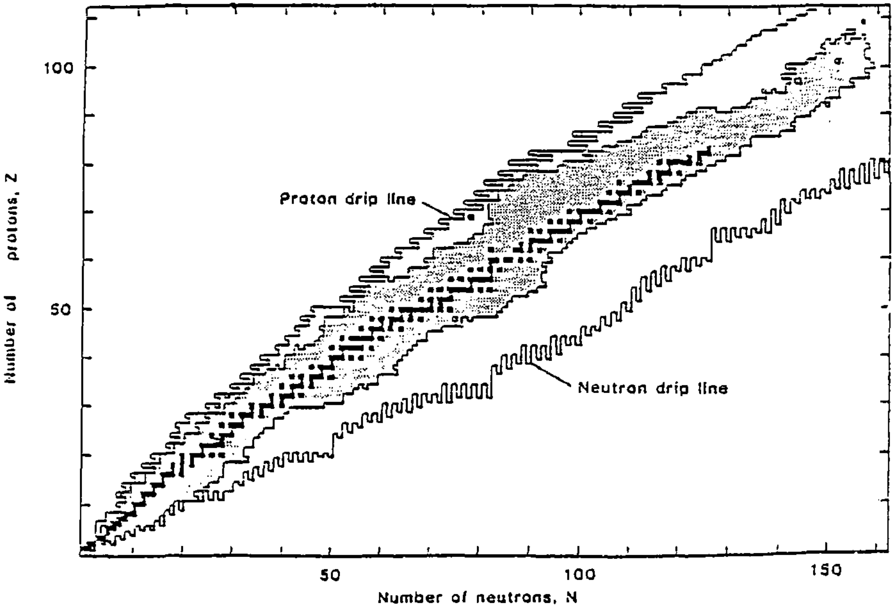


Fig. 1 : Chart of the nuclides (taken in ref.30).
The stable isotopes are represented by black squares. The grey areas are the isotopes which have already been synthesized and identified. White areas are the isotopes that calculations indicate could exist for an observable period of time but have not yet been produced. These white areas are limited by the neutron and proton drip line.

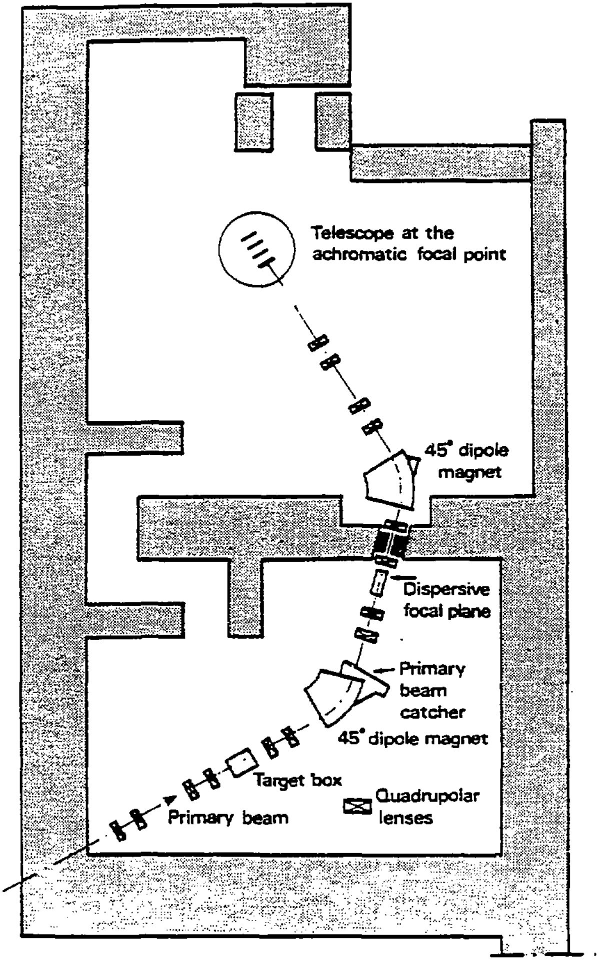


Fig. 2 : General lay-out of the triple-focusing LISE spectrometer in the configuration of the described experiment.

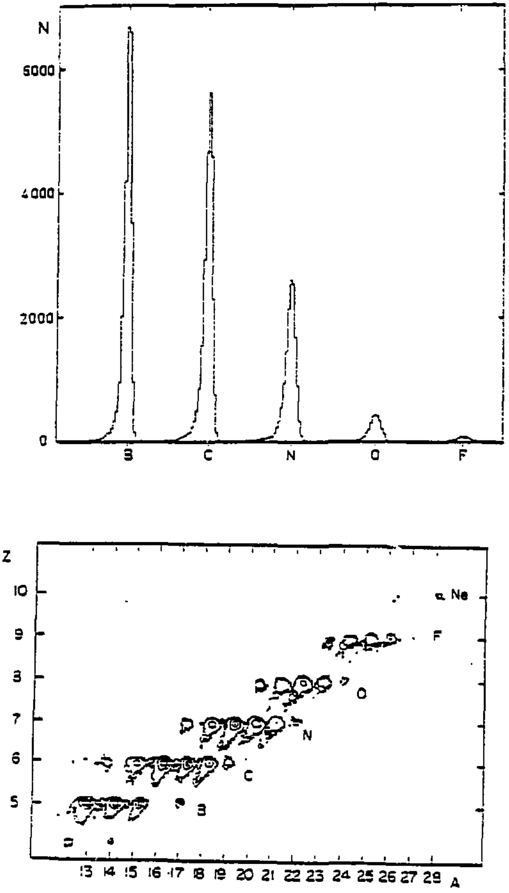


Fig. 3 : a) Z histogram for all the fragments collected at Bρ = 2.66 Tm in the Ar (44 MeV/u) + Ta collision.

b) Z and A identification diagram for all the fragments collected at Bρ = 2.66 Tm in the Ar (44 MeV/u) + Ta collision.

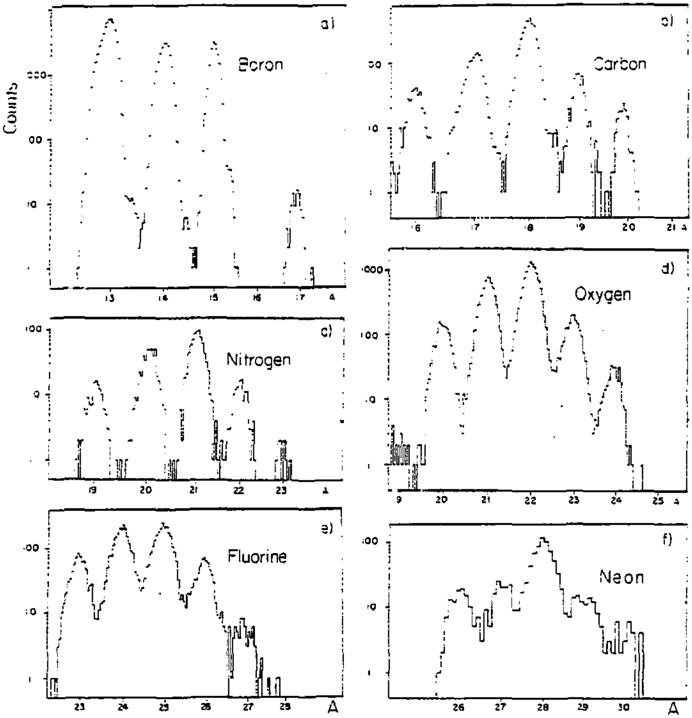


Fig. 4 : Mass histograms of neutron rich isotopes for boron a) carbon b) nitrogen c) oxygen c) oxygen d) fluorine e) and neon f). Histograms a) d) e) and f) were obtained at Bρ = 2.66 Tm and b) et c) at Bρ = 2.92 Tm.

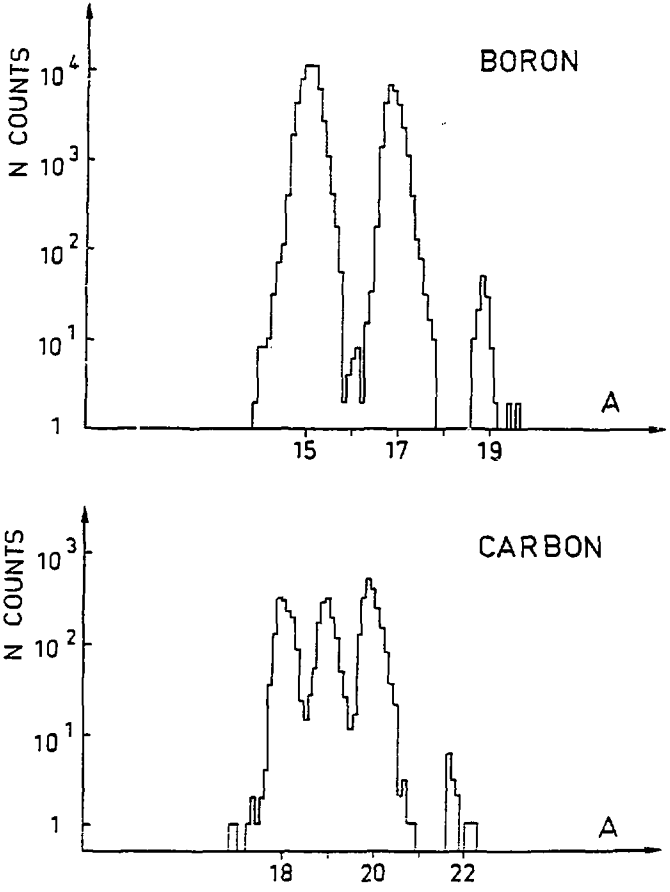


Fig. 5 : Calculated mass distributions for boron and carbon isotopes, summed over all the LISE settings used in the experiment ($B\rho$ = 3.20 Tm, $B\rho$ = 3.10 Tm, $B\rho$ = 3.00 Tm).

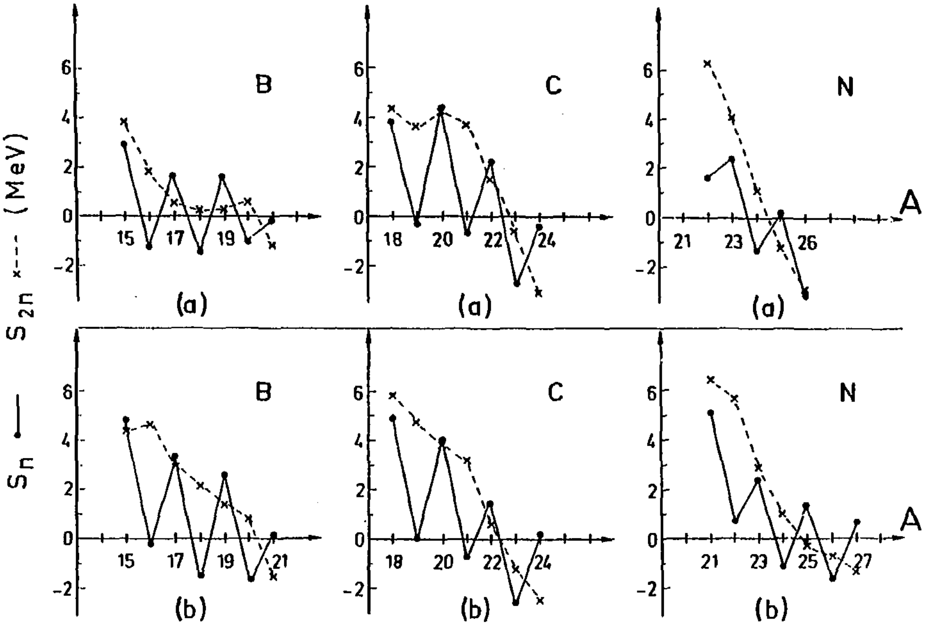


Fig. 6 : Predicted one and two-neutron binding energies (Sn, S_{2n}) for B, C and N isotopes according to the formula of (a) J. Janĕcke15) (b) M. Uno and M. Yamada13).

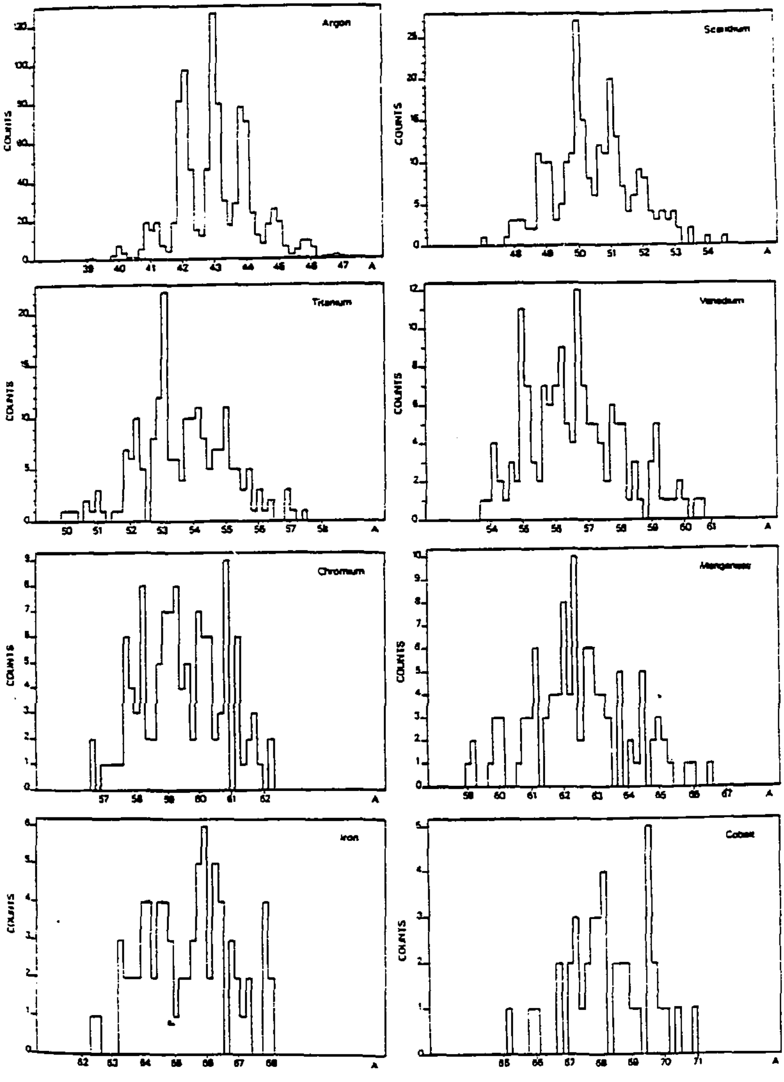


Fig. 7 : Mass histograms of neutron-rich isotopes of scandium, titanium, vanadium, chromium, manganese, iron and cobalt, from the irradiation of the titanium target by 35 MeV/u krypton projectiles. The argon spectrum is the sum of the spectra obtained with the tantalum and the titanium targets.
Since the observed yield of an isotope is a convolution of the acceptance of the spectrometer and of the velocity spectrum due to the reaction mechanism , it does not represent a relative production cross-section.

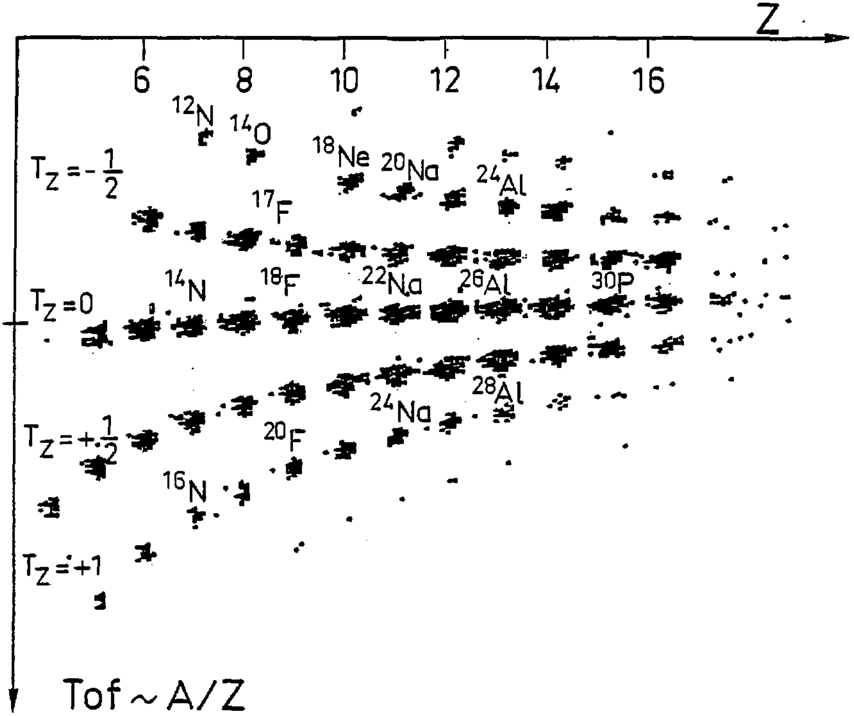


Fig. 8 : Bidimensional plot of time of flight versus Z obtained in the ^{40}Ca (77 MeV/u) + Ni collision at Bρ = 2.10 Tm. This plot exhibits characteristic curves labelled by their isospin projection Tz. One can note the absence of ^{16}F in the Tz = -1 line.

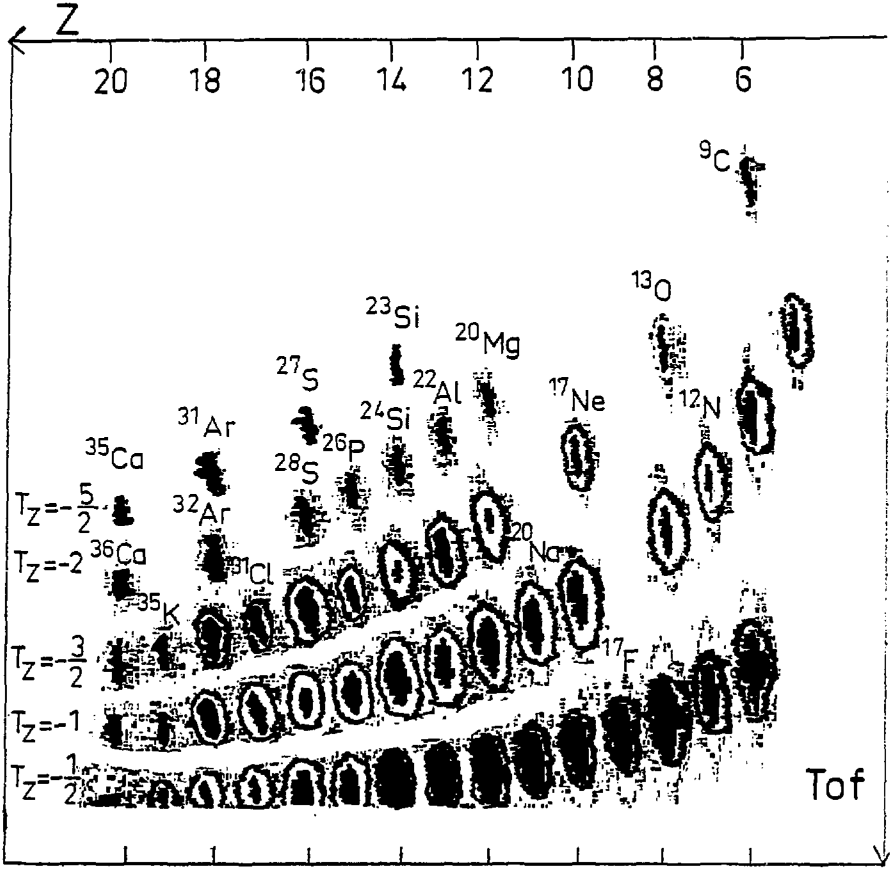


Fig. 9 : Bidimensional plot of time of flight versus Z (idem fig. 8) centered on the proton rich nuclei, after 14 hours of integrated beam. The new Tz = -5/2 nuclei are clearly observed.

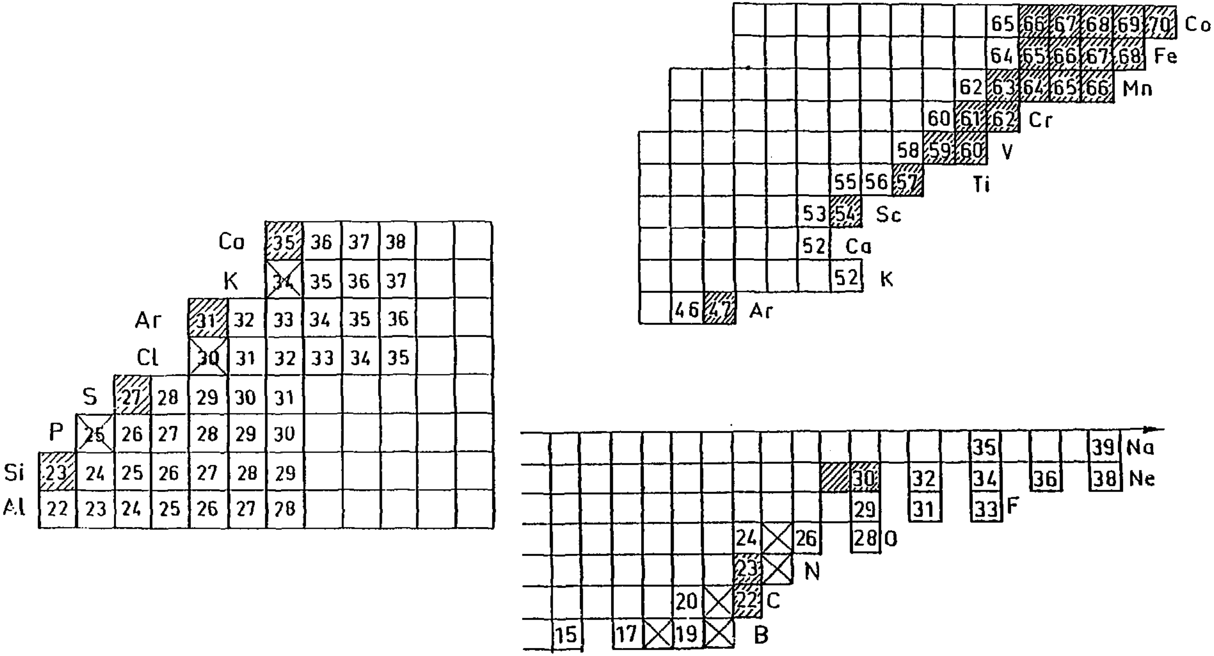
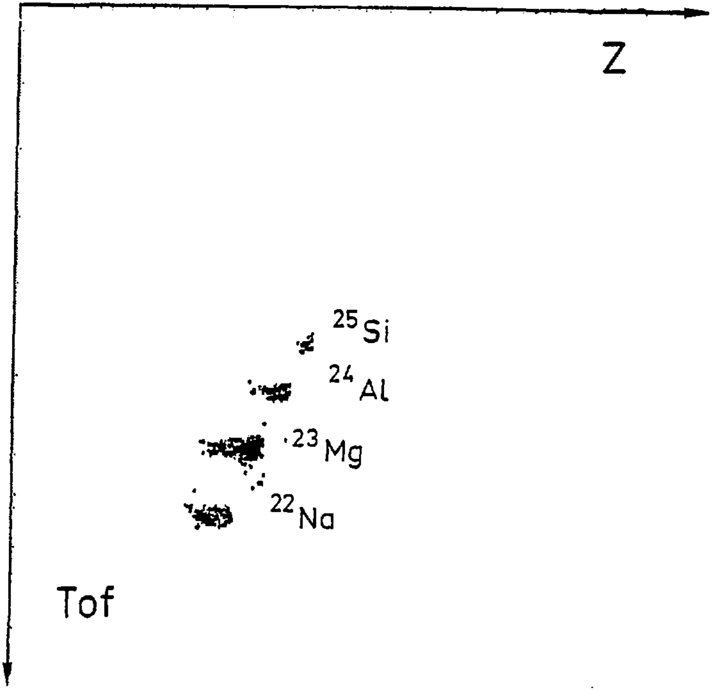


Fig. 10: Partial view of the chart of the nuclides which summarizes results obtained in these experiments. New nuclei shown to be stable against nucleon emission are dashed squares and new nuclei shown to be unstable are crossed squares.



<u>Fig. 11</u> : Bidimensional plot of time of flight versus Z obtained in the ^{40}Ca (77 MeV/u) + Ni collision, with a thick energy degrader and $B\rho_1 = 2.10$ Tm, $B\rho_2 = 1.70$ Tm.