

THE LISE SPECTROMETER AT GANIL

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The doubly achromatic spectrometer LISE is available at the French national heavy ion accelerator GANIL. Experimental results, obtained in radioactive beam production and search for new exotic nuclei are briefly reported.

Introduction

The LISE spectrometer, installed at GANIL, was designed for the production of secondary beams with good optical properties [1]. LISE (Ligne d'Ions Super Epluchés) means highly-stripped ion beams. Fully-stripped or hydrogen- and helium-like heavy ion species of great interest in atomic physics can be produced with LISE. But this spectrometer is also very useful for research of nuclei far from stability.

The experimental setup and improvements are described in section 2. In section 3, I shall explain the production of secondary beams and the results obtained near the proton drip line above $Z = 20$. Finally, a chart of nuclides with all the exotic nuclide results, obtained at GANIL, is presented.

2. Experimental setup

2.1. General features of the LISE spectrometer

LISE is a doubly achromatic spectrometer (fig. 1), in angle as well as in position; this ensures, to first order, a constant flight-path length ($\Delta l/l \approx 10^{-3}$, $l = 18$ m for the total momentum acceptance $\pm 2.5\%$) between the production target and the detector position. Thus the measurement of the time-of-flight is an important parameter in particle identification.

For the purpose of these Proceedings, I shall describe briefly LISE and its main characteristics. More details can be found in refs. [1-3].

The primary beam is focused onto the production target T using 4 quadrupoles q_1 to q_4 (see fig. 1). Up to ten different targets can be mounted on a water-cooled copper wheel. The target can be changed by remote control without entering the experimental area.

Secondary products emitted at 0° are analysed or dispersed as A/Z , by the first section of the line composed of the first dipole D_1 and the quadrupoles lenses Q_1 to Q_4 . Remote controlled variable aperture

slits are located at the intermediate dispersive focal plane; they define the B_p acceptance of the line. An additional stripper foil, an energy degrader, or a thin position-sensitive detector can be placed behind these slits.

The second dipole D_2 associated with the quadrupole lenses Q_5 and Q_6 compensates the dispersion of the first section. Such a system is doubly achromatic, in angle as well as in position. The quadrupole lenses Q_7 to Q_{10} are used to focus the products at the final focal point of the experimental area where the detectors are located.

In order to protect the sensitive detectors from radiation, the first dipole D_1 is a large C-type magnet which allows primary beam catching far away from the transmitted beam. A concrete shielded wall separates the physics detectors from the primary beam catcher. Any unchecked change of the dipole magnetic field is detected by pick-up coils and instantaneously, a Faraday cup is inserted into the primary beam.

An on-line computer controls and actuates all the elements of the spectrometer: magnets, slits and beam diagnostics. The main characteristics of the line are given in table 1.

2.2. Beam diagnostics - intensity measurements

The primary beam intensity can be monitored at several places of interest using Faraday cups or with an inductive intensity monitor.

The spatial distribution of such relatively intense beams can be measured using multiwire secondary emission monitors. On the other hand, low intensity secondary beams are monitored by Ar-CO₂ filled multiwire proportional chambers operating either as ionisation chambers (maximum rate $\approx 10^8$ pps) or as proportional counters (down to 10^3 pps). They have been calibrated using a radioactive α source to give absolute intensities for a given gas pressure and composition, and for various applied voltages [4].

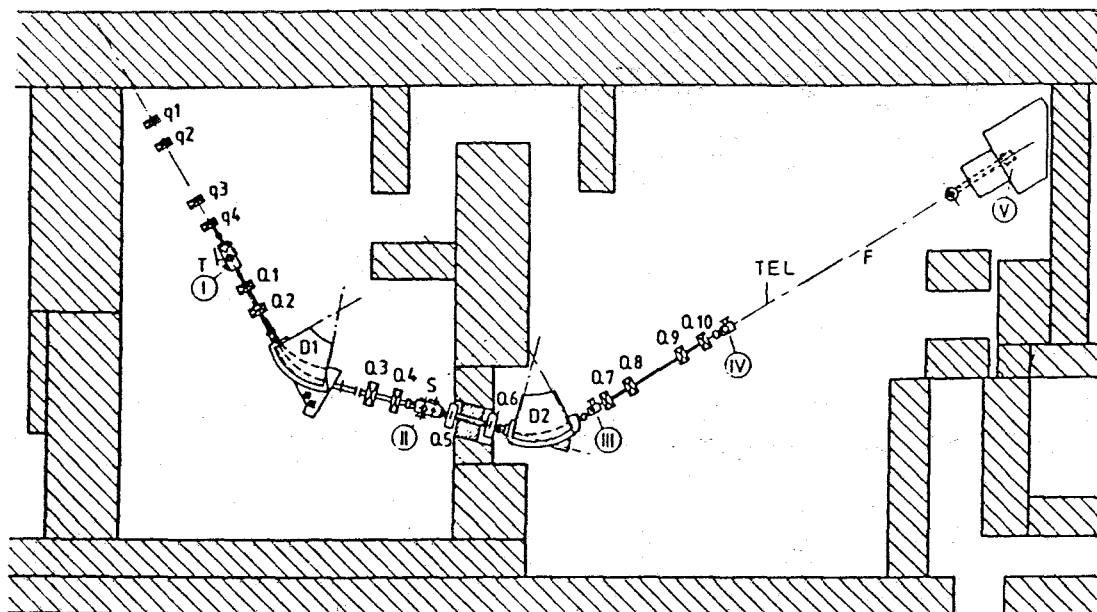


Fig. 1. Experimental setup: the LISE beam line. The symbols q_1 to q_4 , and Q_1 to Q_{10} refer to quadrupoles, D_1 , D_2 to dipoles. The target is denoted by T, the slits by S, the achromatic focal point by F, and the telescope by TEL. Faraday cups are placed at points I, II, IV, V, and beam diagnostics (secondary emission and ionization chambers) at points I, II, III, IV and V.

2.3. Energy degrader as a selection tool

An energy degrader installed in the dispersive focal plane performs a supplementary selection in $Z^{1.5}/A^{2.5}$ due to a differential slowing down in the degrader. The degrader used (aluminium, 295 mg/cm^2) must be of variable thickness in order to compensate for the energy spread and preserve the optical properties of LISE. By tuning the second dipole for some selected nuclei, four or five nuclei are focused at the focal point. An example of the selectivity due to a thick energy degrader is shown in fig. 2. This powerful method, essential for the production of secondary beams with a high purity [5,6], is also currently used by the Bordeaux-GANIL collaboration [7-9] which operates LISE as a Projectile Fragmentation Isotope Separator (PFIS) for spectroscopic decay studies of exotic nuclei.

2.4. Thin position sensitive detector to improve the mass resolution

A parallel plate avalanche counter (PPAC) [3] can be placed in the intermediate focal plane of the first dipole to give a very good determination of the position of the ion trajectory at this point and thus determine the magnetic rigidity. An excellent mass resolution ($\Delta A/A = 0.45\%$ at $A = 37$ for a slit aperture of $\pm 50 \text{ mm}$) is obtained, as shown in fig. 3.

2.5. Sextupole to improve the beam separation at the intermediate focal plane

The intermediate dispersive focal plane has a slope of only 20° compared to the beam axis. This slope increases the beam size and thus degrades the sep-

Table 1
Characteristics of the LISE beam line

Solid angle	$\Omega = 1 \text{ msr}$
Maximum rigidity	$B\rho_{\text{max}} = 3.2 \text{ Tm}$
Dipole deflection angle	$\theta = 45^\circ$
Central trajectory radius	$\rho = 2 \text{ m}$
Dispersion in focal plane	$D = \Delta x / 100(\Delta B\rho / B\rho) = 18 \text{ mm}$
Maximum slit aperture	$S_{\text{max}} = \pm 50 \text{ mm}$
Corresponding maximum $B\rho$ acceptance	$\Delta B\rho / B\rho = \pm 2.717\%$
Total distance from target to achromatic focal point	$L = 18 \text{ m}$

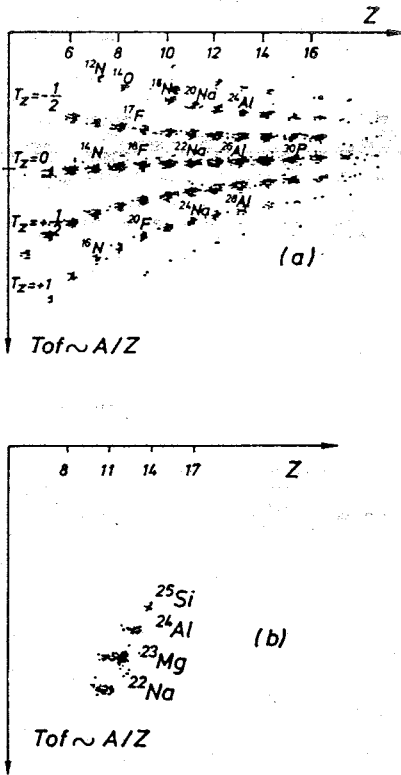


Fig. 2. Two-dimensional plot of time-of-flight versus Z obtained in the ^{40}Ca (77 MeV/u) + nickel collision: (a) without energy degrader at $B\rho = 2.10$ Tm, (b) with a thick energy degrader (aluminium, 295 mg/cm²) and the value of $B\rho_1 = 2.10$ Tm; $B\rho_2 = 1.70$ Tm.

aration at this location. A sextupole placed at the intermediate focal plane rotates the focal plane to be approximately normal (more than 70°) to the beam axis and improves the separation [10].

3. Experimental results

A projectile-like fragmentation process in the intermediate-energy domain can produce nuclei far from the stability. These products have a velocity close to the projectile velocity and are strongly emitted in the forward direction [11]. The LISE spectrometer is well-suited to collect new exotic nuclei produced with these properties.

To optimise production of secondary beams, as well as to study new exotic nuclei, a good choice of target, projectile, and beam energy is needed. This choice can be made by using a simple abrasion-ablation-model which includes a deexcitation stage of the primary distribution [11].

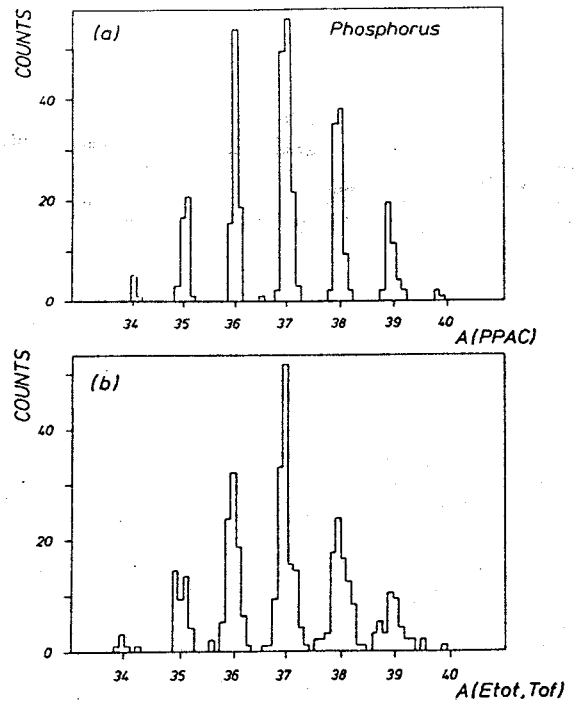


Fig. 3. Mass histograms of phosphorus isotopes (a) using the $B\rho$ value obtained with a parallel plate avalanche counter ($\Delta A/A = 0.45\%$ for $A = 37$) (b) calculated with the following parameters: the total energy E_{tot} and the time-of-flight TOF determined from the signal of the ΔE -detector and the ratio frequency (RF) signal of the last cyclotron ($\Delta A/A \sim 0.6\%$ for $A = 37$).

3.1. Secondary radioactive beams

For the fragments rather close to the projectile mass, the LISE spectrometer can deliver radioactive beams with a good energy resolution and a small amount of contamination [5,6]. The yields I/I_0 (secondary/primary beams intensity) obtained with 44-MeV/u ^{40}Ar and 65-MeV/u ^{18}O are summarized in table 2.

High beam purification is obtained by:

- choosing the right target material and thickness; beryllium targets are more efficient by a factor 2.5 relative to aluminum and 5 times better than nickel targets for the production of secondary beams which have masses close to that of the projectile.
- reducing the $B\rho$ acceptance of the line (i.e. of the slit aperture) in order to better separate the isotopes in a $\Delta E-E$ plot (see fig. 4)
- adjusting the $B\rho$ value (see fig. 5)
- placing a thick energy degrader in the intermediate focal plane and by tuning the magnetic field in the second dipole to retain the acromaticity of the line (see fig. 6).

Table 2

Production yields (I/I_0 for various secondary beams obtained from ^{40}Ar and ^{18}O primary beams

Primary beam	Target	Secondary beam	I/I_0	Secondary beam	I/I_0	Secondary beam	I/I_0
44 MeV/u ^{40}Ar	99 mg/cm ² Be	^{41}K	5×10^{-5}	^{38}Ar	10^{-4}	^{39}Cl	10^{-4}
65 MeV/u ^{18}O	567 mg/cm ² Be	^{18}N	2×10^{-6}	^{39}Ar	3×10^{-4}	^{38}S	0.6×10^{-5}
65 MeV/u ^{18}O	1026 mg/cm ² Be	^{17}N	$\sim 10^{-4}$	^{16}C	2×10^{-6}	^{13}B	1.5×10^{-6}
		^{17}N	5×10^{-6}	^{15}C	4×10^{-6}	^{12}B	10^{-6}
				^{16}C	0.5×10^{-6}		

3.2. Production and identification of new proton-rich nuclei.

3.2.1. Identification techniques

For the identification of exotic fragments, the detection system consists of a standard solid-state detector telescope (300 μ , 1000 μ , 1000 μ , 4000 μ) placed at the final focal plane of LISE. The time-of-flight (TOF) for each fragment is measured between the target and the telescope by signals derived from the ΔE detectors and the radio-frequency (RF) of the last cyclotron stage. The energy information from the telescope, the time-of-flight, and the magnetic rigidity ensures an overdetermined identification of the fragment mass A and atomic number Z .

The particle identification is unambiguously achieved when looking at the two-dimensional plot (see fig. 7) of $\sqrt{\Delta E}/\text{TOF}$ (i.e. Z) versus time-of-flight (i.e. A/Z). This plot exhibits characteristic curves that are related to a given isospin projection T_z . The line of constant

TOF, corresponding to $T_z = 0$, $N = Z$ self-conjugate nuclei, correlates with the absence of the well known unbound nuclei ^8Be ($T_z = 0$), ^9B ($T_z = -\frac{1}{2}$) and ^{16}F ($T_z = -1$) to readily assure the Z and A calibrations.

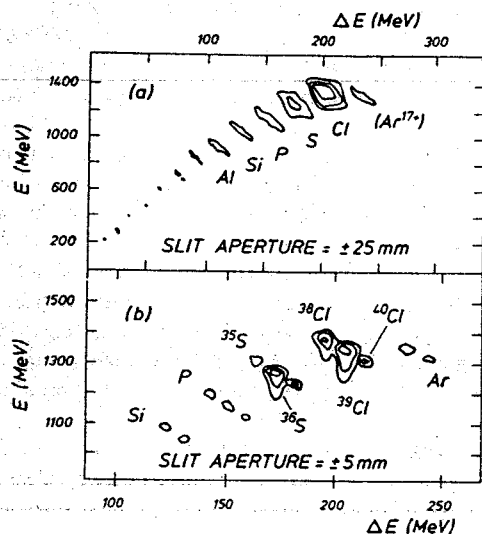


Fig. 4. Beam purity measurements obtained for a 99-mg/cm² beryllium target, and $B\rho = 1.938$ Tm (a) Two-dimensional plot $E - \Delta E$ for a slit aperture of ± 25 mm ($\Delta B\rho/B\rho = \pm 1.4\%$), (b) Same as (a) for a slit aperture of ± 5 mm ($\Delta B\rho/B\rho = 0.28\%$).

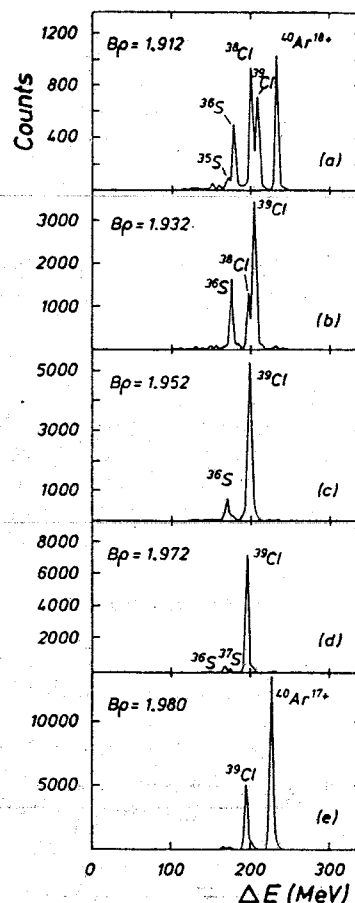


Fig. 5. Effect of a $B\rho$ variation on the ^{39}Cl secondary beam purity. The beam compositions are shown for 5 different $B\rho$ values (in Tm). The ordinate scales correspond to arbitrary units. The $B\rho$ value of 1.972 Tm gives the best purity (84%) for the ^{39}Cl secondary beam; the main contaminants ^{40}Cl (4%), ^{36}S (4.5%) and ^{37}S (3%) are indicated close to the corresponding peaks.

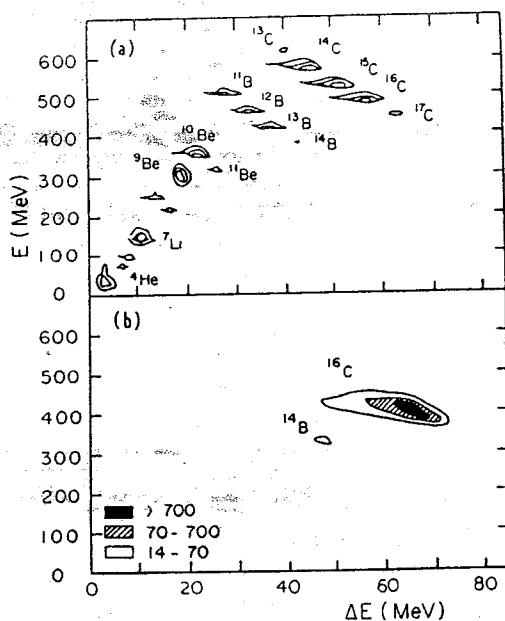


Fig. 6. Two-dimensional plot showing the isotopic composition of a secondary beam obtained in the following conditions: 65-MeV/u ^{18}O + 1036-mg/cm 2 beryllium: (a) unpurified beam ($B\rho_1 = 2.248$ Tm, $\Delta B\rho/B\rho = \pm 0.22\%$); (b) ^{16}C -purified beam ($B\rho_1 = 2.248$ Tm, 150 mg/cm 2 Al intermediate degrader, $B\rho_2 = 2.114$ Tm, $\Delta B\rho/B\rho = \pm 2.78\%$).

3.2.2. New proton-rich nuclei

The series of the $T_z = -\frac{1}{2}$ nuclei (^{23}Si , ^{27}S , ^{31}Ar and ^{35}Ca) predicted to give the limits of the proton drip line

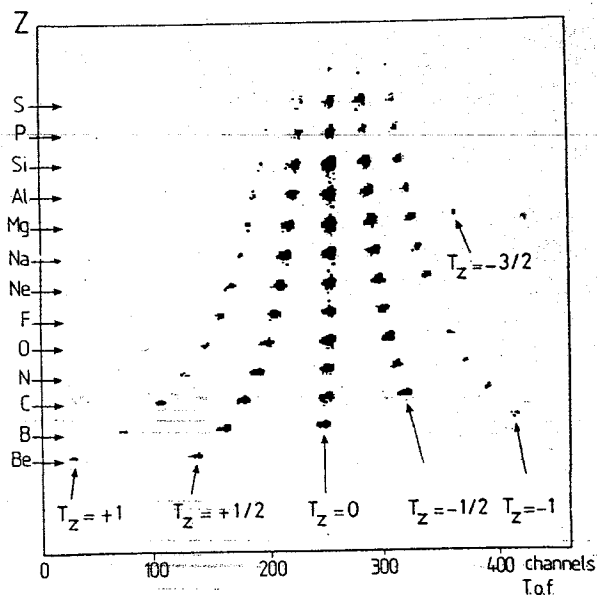


Fig. 7. A two-dimensional plot of Z versus time-of-flight (see also text).

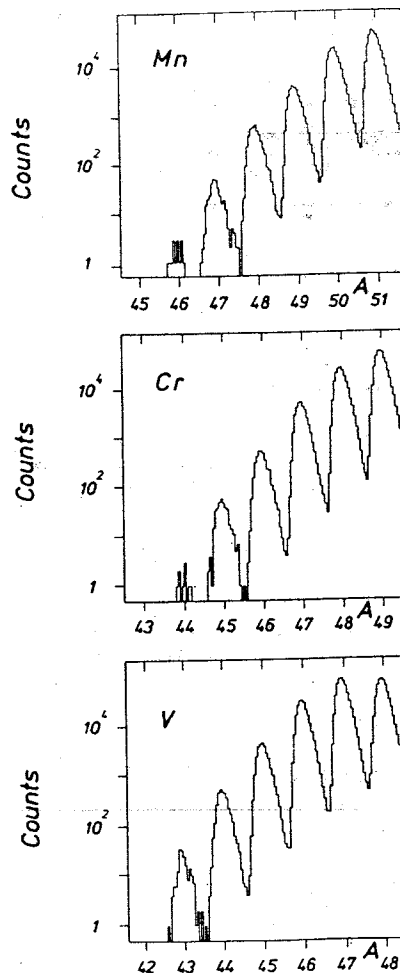


Fig. 8. Mass-distributions for the elements vanadium, chromium and manganese. They have been obtained by summing up the data at different magnetic rigidity settings: $B\rho = 1.80$, 1.85 and 1.90 Tm. Thus, 181, 9, 334 and 15 events are observed for ^{43}V , ^{44}Cr , $^{46,47}\text{Mn}$, respectively.

has been experimentally seen [13] (^{35}Ca was first identified by its β -delayed $2p$ activity [22]). With the possible exception of ^{22}Si , one may assume that the proton drip line predicted by the mass relation of Garvey and Kelson [14] is mapped experimentally up to $Z = 20$.

The proton-rich projectile ^{58}Ni (55 MeV/u) beam has been used to investigate the proton drip line towards higher atomic numbers. Two targets, nickel (92 mg/cm 2) and aluminum (60.4 mg/cm 2), have been bombarded.

Results indicate the bound character of ^{43}V , ^{44}Cr , $^{46,47}\text{Mn}$, (see fig. 8), and ^{48}Fe , $^{50-52}\text{Co}$, $^{51,52}\text{Ni}$, $^{55,56}\text{Cu}$ (see fig. 9). The observation of these new copper isotopes demonstrate clearly that, for the intermediate energy domain, not only the projectile fragmentation

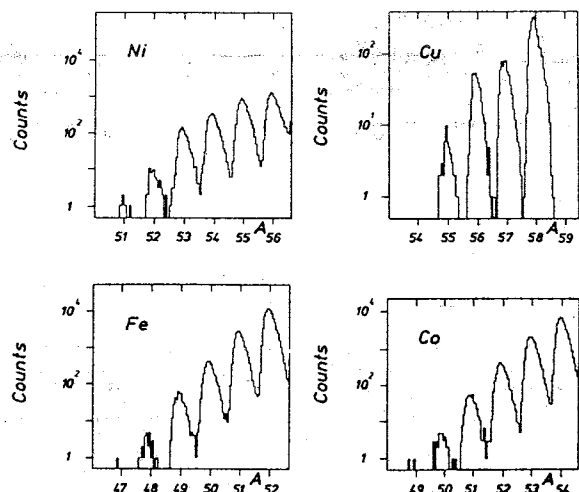


Fig. 9. Mass distributions for the elements iron, cobalt, nickel ($B\rho = 1.80, 1.85$ and 1.90 Tm) and copper ($B\rho = 1.90$ and 1.95 Tm). Thus 27, 36, 442, 3232, 7, 68, 49, 380 events are observed for ^{48}Fe , $^{50,51,52}\text{Co}$, $^{51,52}\text{Ni}$ and $^{55,56}\text{Cu}$.

process but also transfer reactions produce new exotic nuclei. For the odd elements $Z = 23, 25, 27, 29$, these results are in agreement with the predicted position of

the drip line calculated by the mass relation of Garvey and Kelson [14], modified by Janecke [15] using the most recent experimental masses [16], but one must be cautious before making any definite statement on whether or not the drip line has been reached for these odd isotopes, owing to the steepness of the valley of β stability on the proton-rich side.

4. Conclusions

All the new exotic nuclei [13,17–19], half-lives [7–9] determined at LISE and the results concerning the mass measurements [20] performed at the SPEG spectrometer [12] are summarized in fig. 10. This impact in the exotic nuclei domain is made possible by the various and high-intensity beams available at GANIL combined with the properties of the projectile-like fragmentation and the good performance of the spectrometer.

I am grateful to all my colleagues from GANIL and ORSAY for introducing me to the world of exotic nuclear physics. Special thanks are due to D. Guillemaud-Mueller, R. Anne and D. Guerreau for a critical reading of the manuscript and to R. Bimbot for enlightening discussions on secondary beam production.

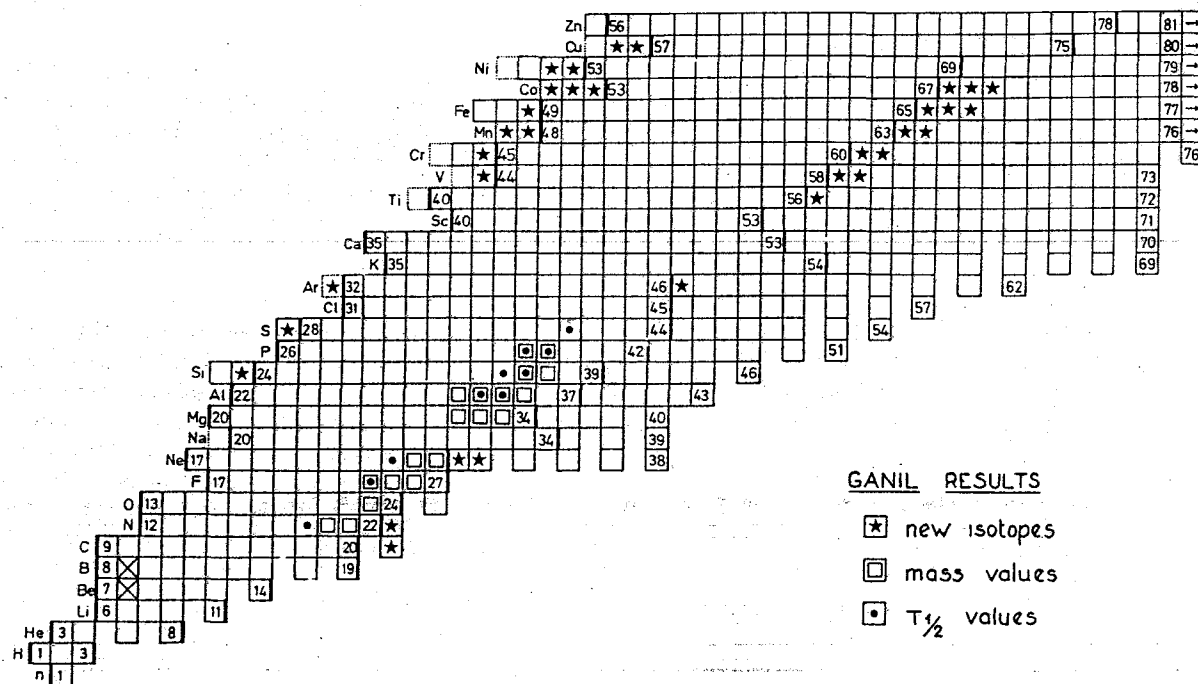


Fig. 10. Summary of experimental measurements performed at GANIL: the bound character of new isotopes, half-lives and mass measurements are indicated respectively by stars, points and squares. The calculated drip lines are also shown by a solid line as predicted by Uno-Yamada [21] for the neutron-rich side and Garvey-Kelson formulae [14,16] for the proton-rich side. Nuclei predicted to be unbound against 1p and 2p emission are represented by dotted lines. The thick lines refer to the last known isotope on both the neutron-rich and the proton-rich sides.

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