EXPLORING OF NEUTRON DRIP LINE

S.M. LUKYANOV
FLNR, JINR, 141980 Dubna, Russia

The study of the properties of neutron-rich nuclei far from stability is one of the most intriguing areas of modern research in nuclear physics. A plenty of the joint GANIL-FLNR experiments were devoted on study of neutron rich unstable nuclei with neutron numbers near the magic shells N=20 and N=28. A lot of interesting results on stability and properties of nuclei in this region were observed during these experiments, mainly performed at GANIL.

The achromatic spectrometer LISE installed at GANIL was used for the production and identification of very neutron- or proton-rich nuclei obtained in the fragmentation of intermediate-energy heavy-ion beams at 0°. The characteristics and advantages of the system are described [1]. Drs. M. Brian and M. Fleury motivated (in the scientific council of GANIL June 4th 1981) to build the LISE magnetic spectrometer with an interest of atomic physics study. It was great and more fruitful idea of C. Detraz, M.Langevin and R. Anne to adjust this fragment spectrometer for nuclear physics.

To exploring neutron drip line, there are two important requirements: on one hand, effective magnetic separator with large angular acceptance and high value of resolution, such as the LISE spectrometer, and on other hand, an exotic beam. The exotic spectrometer was needed for an exotic application by means of exotic beams. Idea of GANIL director Prof. C. Detraz to accelerate a beam of a ^{48}Ca ions was supported by director of our Laboratory Academician G.N. Flerov. A beam of ^{48}Ca ions at rather good quality was already elaborated and obtained at our laboratory. Production of the ^{48}Ca ion beam is the key problem in synthesizing new nuclei. The goal was to achieve the maximum intensity of the ^{48}Ca ion beam at energies E~ 40÷60 MeV/A at a minimal consumption of this enriched of expensive rare isotope. Production and acceleration of ^{48}Ca-beam with an Electronic Cyclotron Resonance ion source were performed successfully [2] by groups of J. Ferme (GANIL) and V. Kutner (FLNR). The world record was obtained: mean rate of consumption of ^{48}Ca was about 2 mg/h and the beam intensity was about 15 μA on charge state 6. Since this method to obtain beam of 48-calcium ions was effectively used for many laboratories (RIKEN Japan, NSCL USA). In 1995, a High Intensity Transport safety system (THI) was studied and validated in 1998 in order to allow sending a several kilowatt beam to a maximum to 200 pnA.

The first experiment on search neutron-rich isotopes in the region of $8 < Z<20$ was carried out in 1988, the harvest was very-very reach [3]. After magnetic separation by the LISE spectrometer, identification through time of flight and $\delta E\times E$ measurements has allowed the observation of the new nuclei, ^{29}F, ^{35,36}Mg, ^{38,39}Al, ^{40,41}Si, ^{43,44}P, ^{45,46,47}S, ^{46,47,48,49}Cl ;^{49,50,51}Ar from the interaction of a ^{48}Ca beam of 55 MeV/u with a tantalum target.

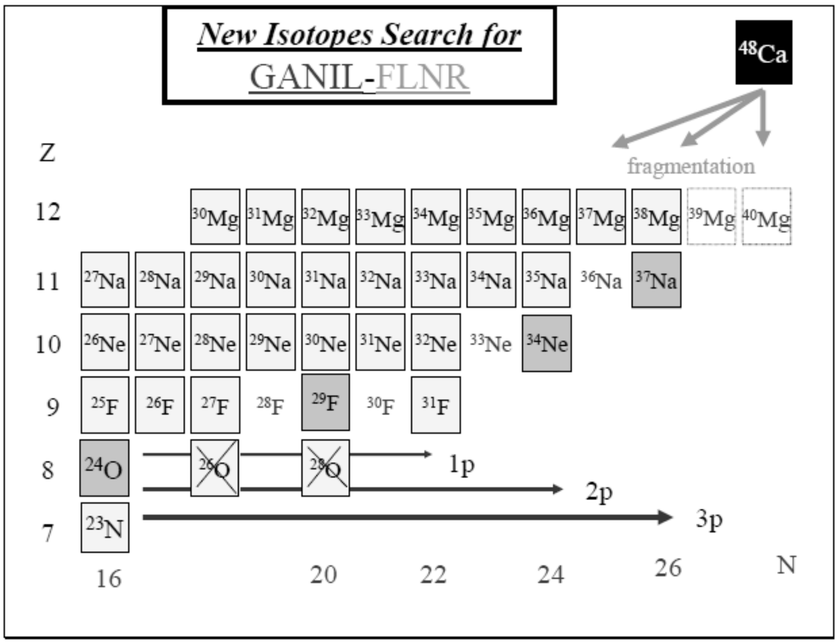

Figure 1. Part of the chart of nuclides obtained in the fragmentation of the ^{48}Ca beam. Experimental evidences of the instability of $^{26, 28}$O were clearly obtained [5, 6]. Particle bound character for ^{29}F , ^{34}Ne, ^{37}Na, ^{35,36}Mg was observed for the first time in the frame of this collaboration and detailed results were published in [4-7].

Among recent results dedicated to explore the neutron drip line in the region elements from O to Mg one could mention the experiments on the particle instability of neutron rich oxygen isotopes ^{26,28}O [5,6] and the discovery of particle stability of ^{34}Ne and ^{37}Na [7]. The appearance of a so-called "island of inversion" with respect to the particle stability of isotopes has been claimed through various theoretical predictions.

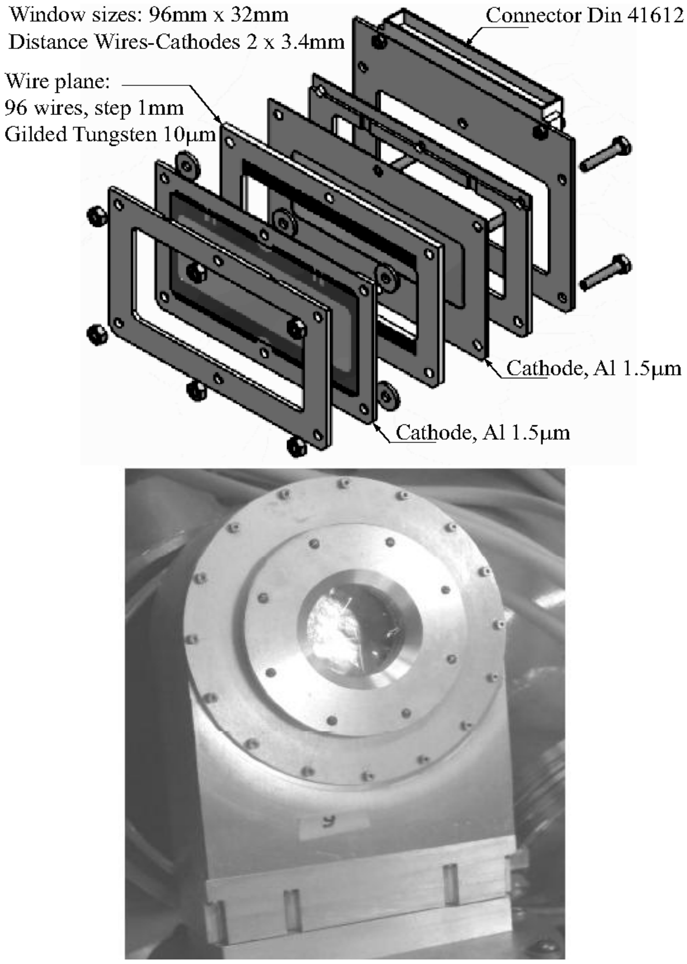

Figure 2. View and schematic presentation of the CAVIAR proportional position-sensitive detector for particle-tracing in the intermediate plane of the LISE spectrometer.

A particular feature in this region is the progressive development of prorate deformation in spite of the expected effect of spherical stability due to the magicity of the neutron numbers N=20 and N=28. It was argued that the deformation may lead to enhanced binding energies in some of yet undiscovered neutron-rich nuclei. The particle instability of $^{26,28}O$ isotopes gives strong evidence on the onset of the deformation in the region. Our pioneer study and clear results on particle unbound character of neutron rich oxygen isotopes $^{26,28}O$ has initiated further studies (both experimental and theoretical) in various Laboratories (in USA, Japan *etc.*). One might expect that the drip line for the fluorine-magnesium elements could move far beyond the presently known boundaries. In our next experiment [7], we had an attempt to determine the neutron drip line for the F-Ne-Mg isotopes in the region of the neutron numbers N=20-28. In particular, our experiment was dedicated to the direct observation of the ^{31}F, ^{34}Ne, ^{37}Na and ^{40}Mg nuclei.

The experiment benefited of a recent update of the LISE spectrometer to the LISE 2000 level. The upgrade includes: an increase of the maximum magnetic rigidity to 4.3 Tm, an increase by a factor of 2.5 of the angular acceptance and a new line with improved optics. In addition to the standard identification method of the fragments via time-of-flight (ToF), energy loss (dE) and total kinetic energy (TKE), a multiwire proportional detector (due to high granularity was called CAVIAR detector by R.Hue (GANIL)) was placed in the dispersive plane of the LISE 2000 spectrometer. This detector allowed to measure the magnetic rigidity of each fragment via its position in the focal plane, improving the mass to charge resolution (A/Q). A spatial resolution of 0.5 mm was achieved for a counting rate of 10^4 particles per second. The mass-to-charge ratio (A/Q) was obtained with an accuracy of 0.8%, which could be consider as an next world record in the experimental technique in heavy ions physics. According to our experimental practice, the CAVIAR is a powerful tool for research and nuclear spectroscopy on nuclides produced with very low cross section, especially concerning to the nuclides closed the proton or the neutron drip-line. In addition, the CAVIAR detector became an important part of the LISE detector system and was very useful for a plenty of the future experiments. The result of the particle identification based only on the dE, ToF, and TKE is shown in Fig.3a, where the energy loss measured in the first detector of the telescope is plotted versus the time of flight (ToF) between the dE silicon telescope and the cyclotron radiofrequency. This matrix was obtained from the data accumulated during 2.5 days with a mean intensity of primary beam of 150 pnA. The new isotopes 34Ne (two events) and 37Na (one event) are clearly visible. The 34Ne and 37Na have also been unambiguously identified by using the calculated value of A/Z . This value was obtained from the ToF and from B□, measured by means of the multiwire detector. Two-dimensional A/Z versus Z plot is shown in Fig. 3b. The presence of the events corresponding to 34Ne and 37Na confirms that these nuclei are bound.

An outstanding issue is following: oxygen isotopes with magic proton number Z=8 could keep only 16 neutrons as maximum, adding one or two protons above Z=8 allows to have got 31F or 34Ne as particle-bound nuclei and to keep 6 or even more additional neutrons inside!

The stability/instability of the present nuclei can be explained by taking into account various degree of mixing in sd and fp shells, which is related to the deformation effects. According to our results, the neutron drip line is extended beyond the N=20 and reaches N=24 for neon and even N=26 for sodium isotopes as a consequence of the mixing of d3/2 and f7/2 states, while the N=20 shell closure disappears.

The nuclei in this region are spectacular examples of shape coexistance between spherical and deformed configurations, for example, 32Mg. In the frame of shell model, the deformed ground state in 32Mg is a consequence of the strong correlation energy of 2p-2h neitron excitations from sd shell to pf for the magnesium. It was suggested that the extra binding energy was gained by the deformation associated with the particle-hole excitation cross the N=20 shell gap. If a nucleus gains binding energy through the deformation, the drip line extends father from the one expected by closed shell. Recent experiment at GANIL were dedicated to the stability study of the neutron-rich nuclei with Z>7 and around N=20. The variation of the shell gap and deformation as a function of N and Z could be a major challenger.

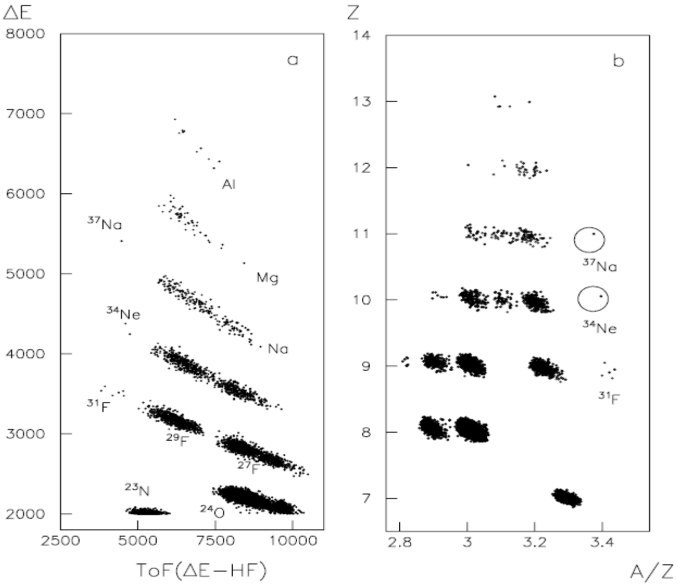

Figure 3. (a) Energy loss versus ToF identification matrix. (b) Two-dimensional A/Z versus Z plot, which was obtained in the reaction of a 58.9 A MeV 48Ca beam on tantalum target. The new isotopes 34Ne (two events) and 37Na are clearly visible

Within a naive shell model picture, magic nuclei are associated with particle configurations where orbits are fully occupied and for which a large energy gap exists at the Fermi surface. For these reasons correlations are hindered in magic nuclei that are characterized by (i) an high excitation energy of their first excited state, (ii) a low transition probability from the ground state to the first excited state, and (iii) a spherical shape. Appearing for the nucleon numbers 2, 8, 20, 28, 50, 82, and 126, magic numbers are the pillars supporting the chart of nuclei usually represented from the proton to the neutron drip lines. However, this picture originating from our knowledge on stable nuclei has to be refined: the spherical magic numbers are now known not to be a valid concept from drip line to drip line. This experimental fact has been first established in the N=20 neutron rich nucleus, 32Mg, in the early 1980 [8]. The first indication of modification in the shell structure of exotic N=28 nuclei south of 48Ca came in the 1990s from the measurement performed, of the unexpectedly short beta decay half-life and high neutron emission probability of 44S (4 protons less than 48Ca) [9]. Fig. 4 summarize these experimental information for even Z isotopes from Ca to Si, with a neutron number ranging from N=20 to N=28. From these pictures, one observes a drastic difference in between the evolution of nuclear structure at N=20 and N=28.

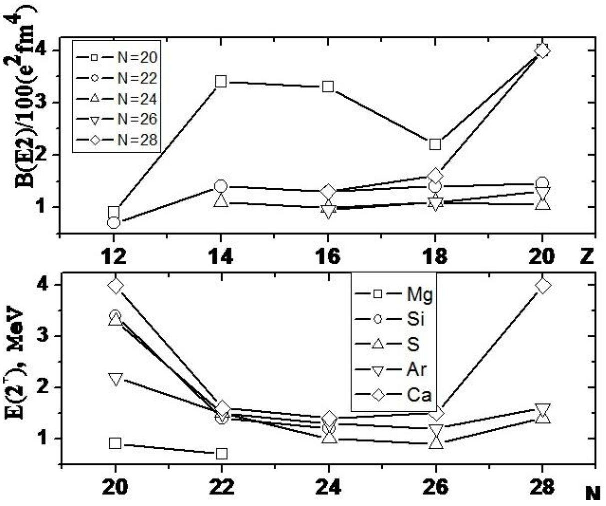

Figure 4. (bottom) Excitation energy of the first 2+ state for the Ca, Ar, S, and Si isotopes from N=20 to N=28. (top) reduced transition probabilities B(E2) for the same isotopes.

While remaining high for each considered N=20 isotones, the excitation energy of the first 2+ state progressively decreases at N=28 when going away from the stable Ca isotone. Similarly, the reduced transition probabilities B(E2) increase at N=28 going farther from 48Ca while keeping a very low value at N=20 [10]. Therefore, there is a great interest to study nuclei in the region of neutron closure N=28. Experimentally, the properties of 44S have been studied and it was concluded there that the ground state of 44S is deformed. This result suggests a significant breaking of the N=28 closure for nuclei near 44S. It should be mentioned that experiments were carried out not only at GANIL, they were performed in parallel in Dubna – in the beginning at the U400 cyclotron and later at the new cyclotron U400M with parameters close to the parameters of GANIL. At the U400 cyclotron a joint experiment was carried out to study the production of different nuclei using 32,34S-beams in the energy range 5-20 MeV/A [11]. The comparison of these results with the ones obtained at GANIL at 60 MeV/A showed that the production cross section of some nuclei at low energies is a few times larger than at intermediate energies. This fact allows to make conclusions concerning the possibilities of producing secondary beams at U400M whose primary beams are of very high intensity. These results may have an important impact on the new concept of the radioactive beam factory in LNR-JINR. It is noteworthy that during 1998 such a factory (the SPIRAL project) starts operation at GANIL. This will allow to start a new-quality collaboration of the Dubna and GANIL physicists and accelerator specialists in this very promising field of nuclear physics.

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