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Abstract

The neutron drip line in neon-magnesium region has been explored by the projectile fragmentation of a 59.8A MeV ^{48}Ca beam using the new fragment separator LISE-2000 at GANIL. New neutron-rich isotopes, ^{34}Ne and ^{37}Na, have been observed together with some evidence for the particle instability of ^{33}Ne and ^{36}Na.

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The experimental determination of the neutron drip line is a milestone for the understanding of the nuclear structure in the region of the $sd-fp$ shells. Among recent results dedicated to explore the neutron drip line in the region of elements from O to Mg one could mention the experiments on the particle instability of the neutron rich oxygen isotopes ^{26,28}O [1, 2, 3] and the discovery of particle stability of ^{31}Ne [4] and ^{31}F [5]. The appearance of a so-called 'island of inversion' with respect to the particle stability of isotopes has been claimed through various theoretical predictions. A particular feature in this region is the progressive development of prolate deformation in spite of the expected effect of spherical stability due to the magicity of the neutron number $N = 20$ [6, 7, 8, 9]. It was argued that the deformation may lead to enhanced binding energies in some of yet undiscovered neutron-rich nuclei. The particle stability of ^{31}F gives a strong evidence on the onset of the deformation in the region. Therefore, one may expect that the drip line for the fluorine-magnesium elements could move far beyond the presently known boundaries.

In this work, we present the results of our attempt to determine the neutron drip line for the Ne-Mg isotopes. In particular, our experiment was dedicated to the direct observation of the ^{34}Ne, ^{37}Na and ^{40}Mg nuclei. These nuclei were searched for among the fragmentation products of a 59.8A MeV ^{48}Ca beam on a 160 μm tantalum target. The very neutron rich beam and target were chosen to optimize the production rate of the drip-line nuclei in accordance with the LISE code [10] and the results of the previous work [11]. The mean intensity of the ^{48}Ca beam was 150 pnA. The experiment benefited of a recent update of the LISE [12] spectrometer to the LISE 2000 [13] 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. As a consequence, a total increase of a factor 10 in the production rate of the drip line nuclei has been achieved with respect to the use of the standard LISE spectrometer. The reaction fragments were collected and analyzed by the LISE 2000 spectrometer operated in an achromatic mode and at the maximum values of momentum acceptance (5%) and solid angle (1.9 msr). The magnetic rigidity of the first half and second half of the spectrometer was set to 3.48 Tm and 3.391 Tm, respectively . To reduce the overall counting rate due to light nuclei a beryllium wedge with a mean thickness of 563 mg/cm^2 was placed at the momentum dispersive focal plane.

In addition to the standard identification method of the fragments via time-of-flight (ToF), energy loss (ΔE) and total kinetic energy (TKE), a multiwire proportional detector 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). The sensitive area of this detector was 10 cm(H)×5 cm(V) covering the full momentum acceptance of the spectrometer. The cathode wires were individually read out. A spatial resolution of 0.5 mm was achieved for a counting rate of 10^4 particles per second. The typical efficiency for this particle detector was about 78%. The mass-to-charge ratio (A/Q) was obtained with an accuracy of 0.8%. The selected fragments were implanted in a telescope consisting of seven silicon detectors for the identification of the fragments. In the data analysis, the fully stripped fragments were selected by putting gates on the total kinetic energy measured with the silicon telescope.

The result of the particle identification based only on the ΔE, ToF, and TKE is shown in Fig.1a, where the energy loss measured in the first detector of the telescope is plotted versus the time of flight (ToF) between the ΔE silicon telescope and the cyclotron radiofrequency. This matrix was obtained from the data accumulated during 2.5 days with a mean intensity of the primary beam of 150 pnA. The new isotopes ^{34}Ne (two events) and ^{37}Na (one event) are clearly visible. The discovery of ^{31}F [5] is also confirmed. The ^{34}Ne and ^{37}Na have also been unambiguously identified by using the calculated value of A/Z. This value was obtained from the ToF and from Bρ, measured by means of the multiwire detector. Two-dimensional A/Z versus Z plot is shown in Fig. 1b. The presence of the events corresponding to ^{34}Ne and ^{37}Na confirms that these nuclei are bound. One event of ^{34}Ne is absent in Fig. 1b due to the fact that the efficiency of the multiwire detector is only 80% for light fragments. No events, which could be attributed to ^{33}Ne, ^{36}Na and ^{40}Mg were observed.

Yields of $N = 2Z$, $N = 2Z + 2$ and $N = 2Z + 4$ nuclei versus the Z-value are shown in Fig. 2. The yield estimations for the fragments were calculated according to the LISE-code [10, 14]. An attempt to describe the experimental distributions of the fragments was undertaken by convolution of a gaussian form of the beam velocity and of an exponetial tail at lower energies. The experimental data were fitted by the same value of σ=107 MeV/c (parameter of the momentum distribution in the convolution) for the three different case $N = 2Z$, $N = 2Z + 2$ and $N = 2Z+4$. For nuclei with $N = 2Z$ and $N = 2Z+2$ we found an agreement between experimental and calculated values. The calculated values for the nuclei with $N = 2Z + 4$ is higher than experimental ones for Z greater than 6.

The most interesting nuclide in this region is ^{40}Mg. No counts attributed to ^{40}Mg have been observed in the present experiment. We estimated the upper limit for the production cross section of ^{40}Mg to be less than 0.06 pb. Due to the limited statistics (see Fig.2), the present experiment do not allow to draw a definite conclusion on the instability of ^{40}Mg. The production cross section for ^{34}Ne and ^{37}Na was estimated to be about 0.17$\pm$0.12 pb and 0.06$\pm$0.06 pb, respectively. The cross section for ^{31}F is estimated to be about 0.7 pb. This value for the production of ^{31}F in the reaction 59.8A MeV ^{48}Ca+^{nat}Ta is about 5 times higher than in the reaction 94.1A MeV ^{40}Ar+Ta [5].

From the theoretical point of view, the description of the light nuclei in the $sd - pf$ shells is an open problem. In particular, the calculation of the binding energy for the very neutron rich isotopes of O, F, Ne and Na is a real challenge. Various theoretical calculations (finite-range liquid drop model (FRLD) [15], two versions of the shell model (SM) [16, 17, 18], relativistic mean field theory [19] and Hartree-Fock model [20]) predict different position of the neutron drip line in this region. For instance, the FRLD model gives a very high binding energy for of ^{40}Mg. In the frame of this model one- and two-neutron separation energies are above 3.4MeV. One may notice that the FRLD model gives correct predictions for stability of ^{31}Ne and ^{31}F, implying nuclear deformation effects for both the macroscopic and microscopic parts. According to the shell model predictions [17], the heaviest bound isotopes in this region are ^{24}O, ^{27}F, ^{34}Ne, ^{37}Na, ^{38}Mg and ^{43}Al. However, a slight modification of the drip line cannot be excluded since ^{37}Na was predicted to be bound only by 250 keV while ^{31}F, ^{40}Mg and ^{43}Al are unbound by 145, 470 and 550 keV, respectively. According to another shell model calculation [16] ^{26}O, ^{34}Ne and ^{40}Mg are the last stable isotopes against two neutron emission, as indicated by their maximal binding energy. Both SM and HF calculations for even-mass O, Ne and Mg indicate a disappearance of shell magic numbers, and suggest an onset of deformation and a shape coexistence in this region.

The stability/instability of nuclei under consideration in the present work can be explained taking into account various degrees of mixing in sd and fp shells, which is related to the deformation effects. According to our results, the neutron drip line extends beyond $N = 20$ and reaches $N = 24$ for neon and even $N = 26$ for sodium isotopes most probably as a consequence of the mixing of the $d_{3/2}$ and $f_{7/2}$ states.

In summary, the neutron-rich isotopes ^{34}Ne and ^{37}Na were observed using the newly upgraded LISE-2000 spectrometer and the reaction ^{48}Ca+^{nat}Ta at 59.8A MeV. Thus, most probably, the neutron drip line has been reached for the neon and sodium isotopes. However, a define conclusion on the position of the drip line will require further experimental efforts.

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Note added: In the beginning of 2002 a similar experiment on the synthesis of new isotopes close to ^{40}Mg was undertaken at RIKEN(Japan) using the RIPS spectrometer. A few events, which could be attributed to the production of ^{34}Ne and ^{37}Na isotopes, were observed in agreement with the results of the present work.

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Figure 1: **1a** Energy-loss versus total-kinetic energy identification matrix. **1b** Two-dimensional A/Z versus Z plot, which was obtained in the reaction of a 58.9AMeV ^{48}Ca beam on a 161 mg/cm^2 tantalum target during a 2.5-days run. The new isotopes ^{34}Ne (two events) and ^{37}Na are clearly visible. No events associated with ^{33}Ne, ^{36}Na and ^{40}Mg were observed.

Figure 2: Isotopic production for nuclei with the neutron number $N = 2Z$, N=2Z+2 and N=2Z+4. The solid lines present the expected yields according to the LISE-code.

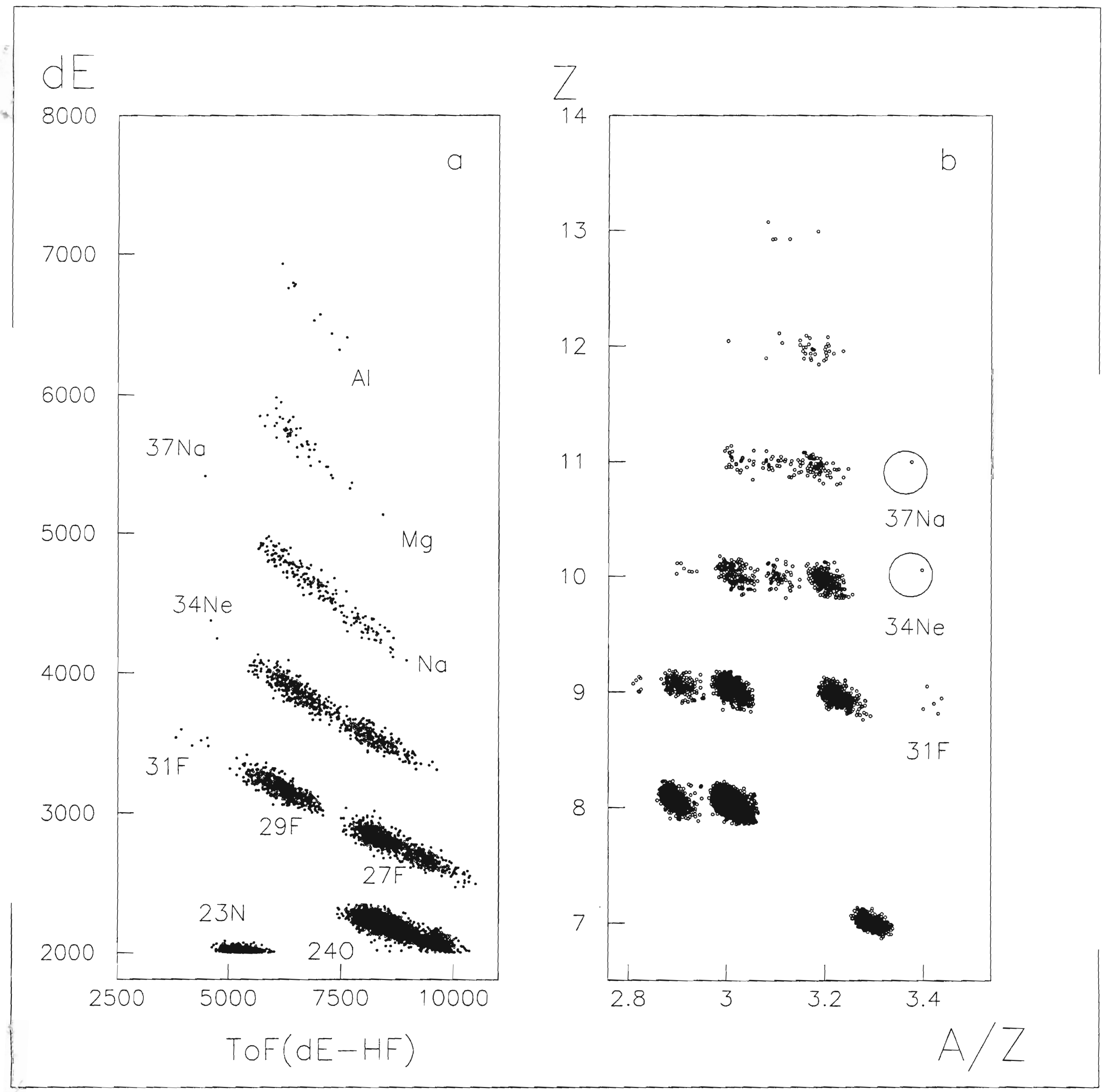
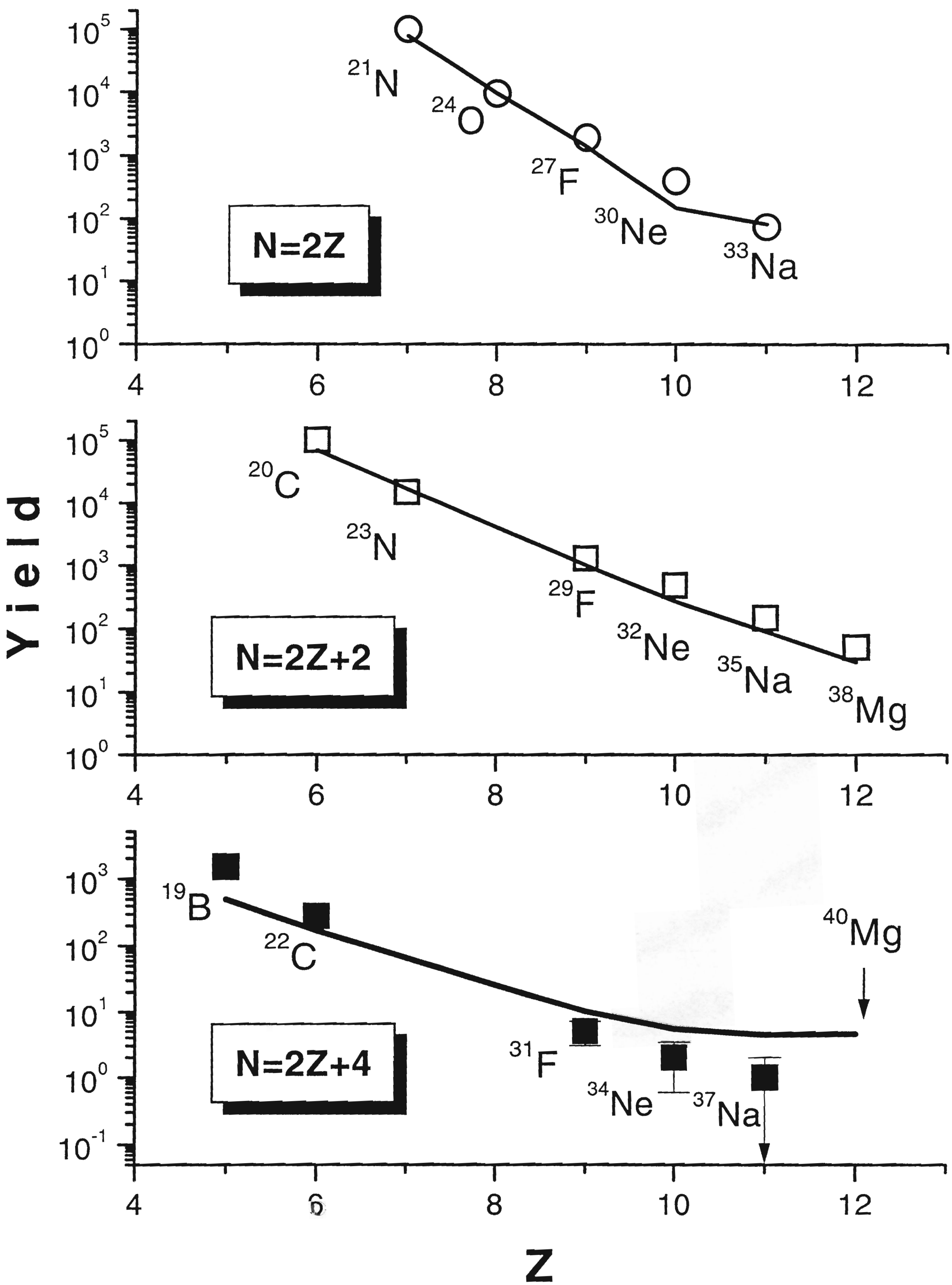

dE
8000
7000
6000
5000
4000
3000
2000
a
Al
37Na
Mg
34Ne
Na
31F
29F
27F
23N
24O
2500
5000
7500
10000
ToF(dE−HF)
Z
14
13
12
11
10
9
8
7
b
37Na
34Ne
31F
2.8
3
3.2
3.4
A/Z

Fig. 1



Yield
Z
N=2Z
N=2Z+2
N=2Z+4
21N
24O
27F
30Ne
33Na
20C
23N
29F
32Ne
35Na
38Mg
19B
22C
31F
34Ne
37Na
40Mg

Fig.2