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RADIOACTIVE ION BEAMS – A TOOL TO STUDY STRUCTURE OF NUCLEI FAR FROM STABILITY[1]

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Using Radioactive Ion Beams new properties of neutron-rich nuclei near the border of stability have been investigated. The structure of these exotic nuclei with Z up to 30 near drip lines has been studied using the elastic scattering of the secondary radioactive neutron-rich beam of ^{11}Li (29 AMeV) on a Si target and the quasi-elastic and inelastic scattering of neutron deficient ^{7}Be and ^{8}B beams (40 AMeV) on a ^{12}C target at GANIL, France. The measurements have confirmed the existence of the neutron halo in ^{11}Li and a proton skin in ^{7}Be and ^{8}B nuclei. The direct measurement of the mass of 31 radioactive nuclei and the derivation of two-neutron separation energies have enabled to establish the new neutron magic numbers $N = 6$ and 16 in the neutron-rich region for the first time instead of normal $N = 8$ and 20 and support the disappearance of the doubly-magic nuclei ^{10}He and ^{28}O. Changes in basic properties of nuclear matter have been confirmed by the novel two step fragmentation in-beam gamma spectroscopy that has established ^{24}O as a new doubly-magic nucleus.

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1 Introduction

Radioactive Ion Beams enable us to study the nuclear structure from the broader insight including in addition to the stable also the unstable radioactive nuclei which are lying in the region of isospin asymmetry with wider neutron/proton ratio, and are far from being accessible with stable beams. In the collaboration with the GANIL laboratory, we have investigated properties of neutron-rich nuclei near the border of stability. Experimental investigation of light exotic nuclei with an anomalous N/Z ratio that lie near the boundary of nuclear stability may give us useful information, since the extreme cases of a nucleon configuration should be more sensitive to the choice of the nuclear potential parameters. The exploration of exotic, short-lived nuclei having large neutron-to-proton imbalance has demonstrated that the "universal" ideas of nuclear properties are in fact not correct. Fig. 1 illustrates how unusual these exotic forms of nuclei called "halo" can be compared to nuclei studied so far. The diameter of the orbits of weakly bound neutrons in the heaviest lithium isotope is compared with the size of a lead nucleus.

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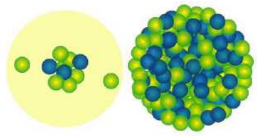

Fig. 1. A scale illustration of the size of the heaviest lithium isotope and a lead nucleus.

The figure illustrates that standard assumptions, such as that the size of a nucleus depends only on the total number of neutrons and protons, are not always valid. Thus light nuclei are a proving ground for probing inter-nucleon forces. The simplest nuclear system having a two-neutron halo is formed by ^{6}He with two loosely bound neutrons that orbit around a compact α particle (^{4}He). But take away one neutron or α particle and the system will immediately fall apart. The two extra neutrons interact together, via a pairing interaction, to make this system of α particle and two neutrons stable. Pairing is a common, yet not well understood feature of nuclei and halo nuclei provide new insights into its origin and nature.

This work has been devoted to the study of two main features of light nuclei i.e. the behaviour of nuclear halo and the change of magicity in neutron-rich region.

2 Halo and skin nuclei

Radioactive ion beams are usually produced by the fragmentation reaction. Stable beams accelerated to energies up to 100 AMeV undergo the fragmentation on Be or C targets and the radioactive reaction products that are collected, selected, and purified by magnetic fragment separators and filters are identified in detectors or can initiate some types of nuclear reactions. At GANIL, we used the doubly-achromatic spectrometer LISE3 to collimate selected ions. Particles scattered from a target were detected by an assembly of silicon strip and BGO detectors.

The elastic scattering of a secondary ^{11}Li beam (29 AMeV) on a ^{28}Si target was measured for the first time [1]. The data were analyzed using both phenomenological and coupled-channel calculations with a double-folding optical potential, with energy- and density- dependent effective interaction and realistic densities. Using coupled-channel calculations with folding potential, a better description is achieved if a neutron halo of ^{11}Li is taken into account. The elastic scattering of the secondary ^{8}B and ^{7}Be beams (40 AMeV) on a ^{12}C target [2] has confirmed the existence of their proton-skin structure. The angular distributions supporting the presence of these structures are shown in Fig. 2 taken from Refs. [1, 2].

3 Magicity at stable and exotic nuclei

The magic numbers expected for a harmonic oscillator mean field potential perturbed by a strong spin-orbit interaction are (2, 8, 20, 28, 50, 82...). Shell structure is experimentally confirmed for beta-stable nuclei, particularly for nuclei called "doubly-magic" i.e. those that have a magic number for both protons and neutrons. Despite of intense effort the search for the ^{10}He (Z=2, N=8) nucleus – the lightest doubly-magic nucleus except the alpha particle – has shown that this nucleus is unbound.

Several experiments searched for the particle stability of ^{28}O – another doubly-magic nucleus. In the last experiment performed at the LISE3 spectrometer at GANIL [3], the fragmen-

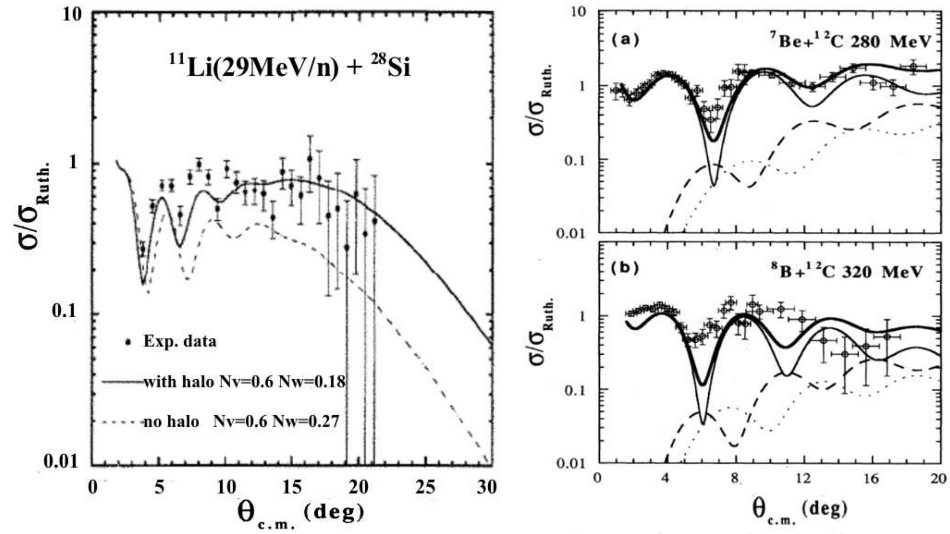

Fig. 2. The elastic scattering angular distributions of ^{11}Li [1], ^{7}Be and ^{8}B on a ^{12}C [2].

tation of the neutron-rich ^{36}S has been used to produce nuclei in this region. No events corresponding to either ^{26}O or ^{28}O were observed. Thus the heaviest experimentally found isotopes with $Z < 9$ were ^{22}C, ^{23}N, and ^{24}O with the same neutron number, N=16.

Consequently, the instability of the two doubly-magic neutron-rich nuclei ^{10}He, ^{28}O and the appearance of deformed nuclei at the so called "island of inversion" observed at the N=20 shell closure were unexpected and a new approach is needed to explain them.

The mass measurements of neutron-rich nuclei between oxygen and calcium using a direct time of flight technique were undertaken at Ganil [4,5]. The masses may provide clear signatures of shell closures and magic numbers. The nuclei of interest were produced by the fragmentation of a 60 AMeV ^{48}Ca beam on a Ta target and two-neutron separation energies derived are displayed in Fig. 3. New data are presented with error bars. The sharp drops at N=22, shown by the dashed vertical line are followed by a moderate decrease as the filling of the next shell starts to influence S_{2n}. These drops correspond to the existence of the shell N_{sh}=20, and are clearly visible practically through all the Si-Ca region. Moreover, the Ca, K and Ar isotopes show also the shell closures at N=28.

To clear up the evolution of two-neutron separation energies in the C-Al region we used the fact that there exist several bound nuclei. Though their masses are not known yet their S_{2n} values must be positive and therefore, we included the estimated S_{2n} values of ^{23}N, ^{22}C and ^{29,31}F bound isotopes to the graph and marked them by circles [6]. Thus the sharp drop of ^{27}F (with 18 neutrons) value is followed by a moderate decrease of S_{2n} values for ^{29}F and ^{31}F and gives us a first clear evidence for the existence of the new shell closure at N=16 for fluorine. Another, even stronger, confirmation of the N=16 shell closure one can get from S_{2n} values for neon isotopes $^{29-32}$Ne [5]. The gaps at N=16 and 6 can be also seen in Fig. 3 (at right) where two-neutron separation energies S_{2n} are plotted versus Z.

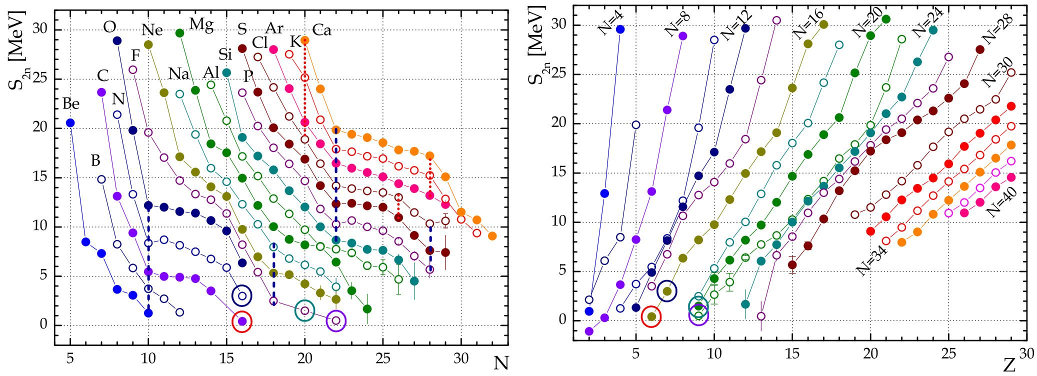

Fig. 3. Two-neutron separation energy S_{2n} versus N (at left) and Z (at right).

The reason why the nuclei near the drip line exhibit some types of deformation also originates from the existence of new magic numbers. As the neutron drip line is approached the magic numbers differ from those encountered near the valley of stability. This fact was also confirmed by in-beam spectroscopy of ^{24}O [7] which was established as a new doubly-magic nucleus. Increased pairing correlations, spin-orbit interaction and the spin-isospin interaction determine the appearance and/or disappearance of various magic numbers.

4 Conclusions

Using Radioactive Ion Beams new properties of neutron-rich nuclei near the border of stability have been investigated. New features as neutron and proton halo structure were studied using the elastic scattering of the radioactive ions. A new shell closure at N=16 has appeared in neutron-rich nuclei for $Z \leq$10 between the $1s_{1/2}$ and $0d_{3/2}$ orbits. This can be accounted for by considering the role of the strong $n-p$ monopole interaction acting between the two spin-orbit partners $\pi d_{5/2}$ and $\nu d_{3/2}$ in a good agreement with Monte Carlo shell model calculations of Otsuka [8]. This fact, strongly supported by the instability of C, N and O isotopes with $N > 16$, confirms the magic character of N=16 for the neutron-rich nuclei in the region 6$\leq Z \leq$10, while the shell closure at N=20 tends to disappear for $Z < 14$.

References

[1] M. Lewitowicz *et al.*: *Nucl. Phys. A* **562** (1993) 301
[2] I. Pecina *et al.*: *Phys. Rev. C* **52** (1995) 191
[3] O. Tarasov *et al.*: *Phys. Lett. B* **409** (1997) 64
[4] F. Sarazin *et al.*: *Phys. Rev. Lett.* **84** (2000) 5062
[5] H. Savajols *et al.*: *Eur. Phys. J. A* **25** (2005) s01, 23
[6] Z. Dlouhý *et al.*: *Nucl. Phys. A* **701** (2002) 189c
[7] M. Stanoiu *et al.*: *Phys. Rev. C* **69** (2004) 034312
[8] T. Otsuka *et al.*: *Nucl. Phys. A* **682** (2001) 155c