New Magic Number, *N* = 16, near the Neutron Drip-Line

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The neutron separation energies (S_n) and the interaction cross-sections (σ_I) for the neutron-rich *p-sd* and *sd* shell region have been surveyed in order to search for a new magic number. Very recently, both measurements have reached up to the neutron drip-line, or close to the drip-line, for nuclei of Z • 8. The neutron-number (N) dependence of S_n shows clear breaks at N=16 near to the neutron drip-line, which shows the creation of a new magic number. A neutron number dependence of σ_I shows a large increase of σ_I for N=15, which supports the new magic number. The origin and influence of the new magic number are also discussed.

1. Introduction

The shell structure is one of the very important quantities concerning nuclear structure. Nuclei show a closed shell structure for the following neutron (N) and proton (Z) numbers: 2, 8, 20, 28, 50, 82 and 126. They are called nuclear magic numbers. The appearance of magic numbers has been explained by Mayer and Jensen at 1949, introducing a spin-orbit coupling.

Recent improvements of radioactive beam (RI beam) technology allow measurements of the mass, half-life, size and other properties of unstable nuclei. Furthermore, nuclear reactions using RI beams have been studied very much [1]. Thus, based on the results, some interesting characteristics of unstable nuclei, such as a halo and a skin, have been revealed. In the points of nuclear magic numbers, the disappearance of some traditional magic numbers has been studied both experimentally and theoretically. For example, the disappearance of the N = 20 closed shell was shown in ^{32}Mg experimentally in terms of a low-lying 2^+ level [2] and a large $B(E2;0^+_1 \rightarrow 2^+_1)$ value [3]. Direct evidence for a breakdown of the N = 8 shell closure was shown for ^{12}Be by studying the one-neutron knockout reaction (^{12}Be, $^{11}Be+\gamma$) on a ^{9}Be target at 78 *A* MeV [4]. Although the disappearance of magic numbers has been discussed, as shown above, no appearance of a magic number has been shown experimentally so far.

From theoretical points of view, the appearance of new magic numbers in a neutron-rich region has been predicted within the framework of the energy-density formalism [5]. The authors in Ref. [5] predicted the appearance of N = 16, 34 and 58 as neutron magic numbers for unstable nuclei, together with a weakening of the shell closure at N = 20 and 28.

2. Search for new magic numbers

Recent improvements of secondary-beam techniques allow us to now measure the mass and the interaction cross-sections (σ_I) for nuclei on the neutron drip-line or close to the drip-line. One of the powerful mass measurements is a direct time-of-flight mass determination. The principle of this technique requires only a determination of the magnetic rigidity and velocity of an ion. That is, for a particle of mass m and charge q traversing through an achromatic system, the magnetic rigidity ($B\rho$) is related to the velocity (v) as $B\rho = mv/q$. Thus, a precise measurement of the rigidity and velocity would allow the mass of an ion to be deduced. Direct mass measurements have reached to the drip-line and near to the drip-line for Z • 8 in a recent mass evaluation [6]. On the other hand, measurements of σ_I can be performed by the transmission method, which have been extensively measured at the projectile fragment separator facility (FRS) at GSI. FRS is the only available RI beam facility for relativistic energies (~1 *A* GeV). Recently, σ_I measurements have reached to the drip-line for Z • 8, except for ^{22}C [7].

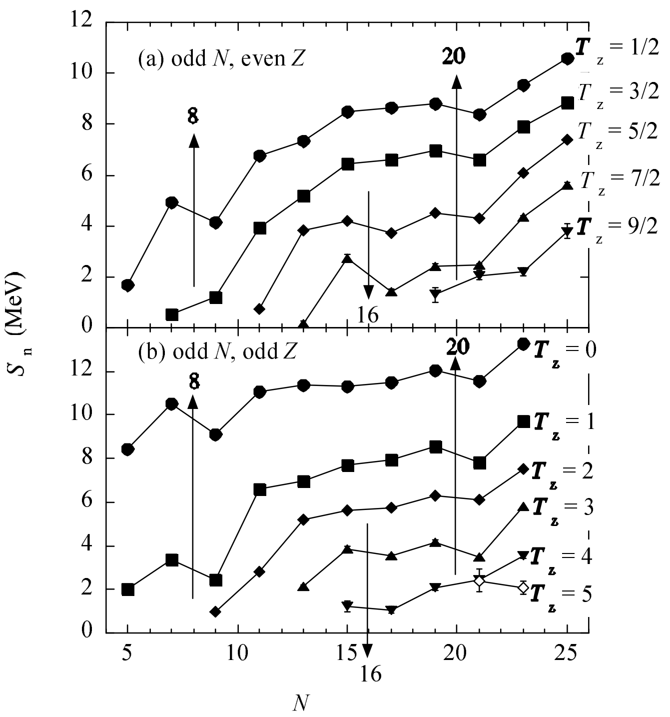

Fig. 1 Neutron-number (N) dependence for experimentally observed neutron separation energies (S).

The neutron-number dependence of experimentally observed S_n for nuclei with odd N and even Z (odd N and odd Z) is shown in Fig. 1 (a) (Fig. 1 (b)), respectively. S_n is defined by the difference of the binding energies (BE) ($S_n(N,Z) = BE(N,Z) - BE(N\text{-}1,Z)$), where BE are determined by recent mass measurements. In Fig. 1, a magic number appears as a decrease of S_n along with an increase of N [8]. The traditional magic numbers (N=8, 20) are clearly seen close to stable nuclei as breaks in the small isospin numbers (T_z) lines. However, the break at N = 8 (N = 20) disappears at neutron-rich T_z = 3/2 (T_z = 4), which is also known concerning other experimental quantities, as discussed above. On the other hand, a break in the S_n line appears at N = 16 for T_z • 3, as clearly shown in Fig. 1, which indicates the creation of a new magic number in N = 16 near to the neutron drip-line.

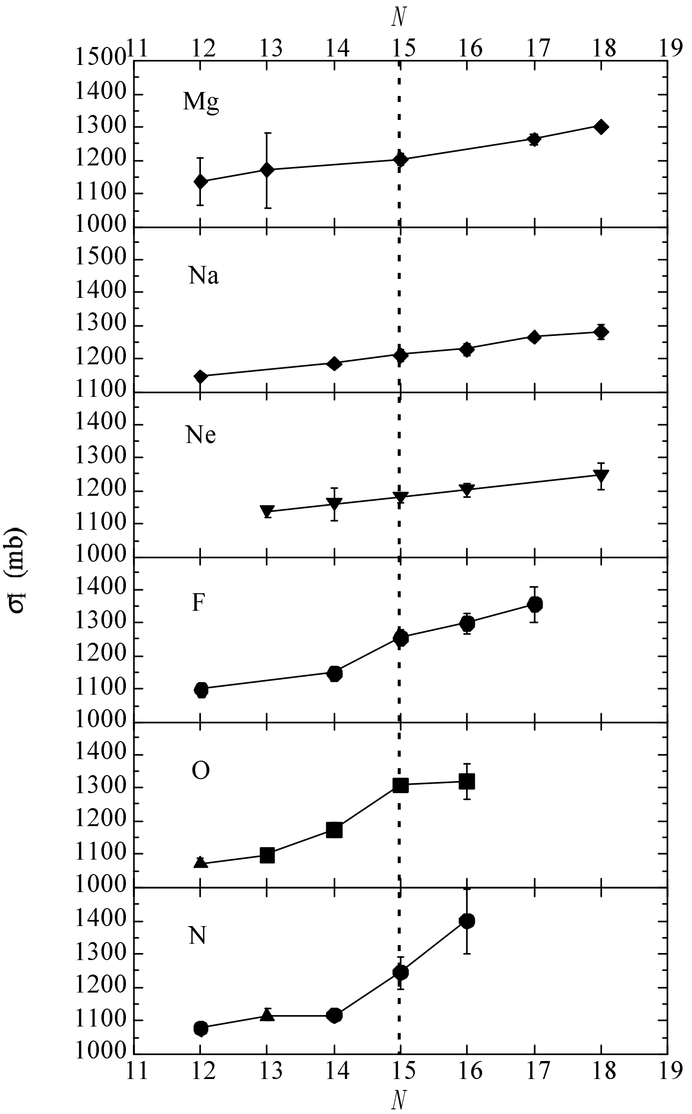

Fig. 2 Neutron-number (N) dependence for experimentally observed interaction cross-sections (σ_I) for N to Mg isotopes on C targets.

In Fig. 2, a neutron-number dependence of experimentally observed σ_I for N to Mg isotopes is shown. A steep increase of σ_I from N = 14 to N = 15 for N to F isotopes, is shown in Fig. 2. On the other hand, for Ne to Mg isotopes, no steep increase of σ_I is shown in Fig. 2, although some σ_I have large error bars. It is noted that a clear difference occurs at T_z = 3, which suggests some correlation for the new magic number N = 16, as shown in S_n. The recent development of a Glauber model analysis for few-body systems allows one to distinguish the single-particle wave-functions for the valence nucleon ($2s_{1/2}$ or $1d_{5/2}$ orbitals) [7]. The results of an analysis show a dominance of the $2s_{1/2}$ orbital for the valence neutron in ^{22}N, ^{23}O and ^{24}F.

On the other hands, in ^{25}Ne, ^{26}Na and ^{27}Mg, the nature of a mixing of $2s_{1/2}$ and $1d_{5/2}$ orbitals is shown. Thus, a valence neutron in the N = 15 chain shows the following tendency: the purity of the $2s_{1/2}$ orbital is larger when T_z is larger. This conclusion supports the creation of a new magic number at N = 16 near to the neutron drip-line, since a clear single-particle structure is suggested for N = 15 nuclei near to the neutron drip-line.

3. The origin of the new magic number

The origin of this new magic number may be due to neutron halo formation. Fig. 3 shows the single-particle orbitals of a neutron in the normal spherical Woods-Saxon potential. The single-particle orbitals were calculated for A/Z = 3 nuclei just to show the effect of neutron excess (A is the mass number). Normal shell gaps N=8, 20, 28 are seen in the region for a binding energy of about 6 to 8 MeV, as expected. However, for a weakly bound system in A/Z = 3 nuclei, the spacing, and even the ordering, of the orbitals changes. The most pronounced is the s orbital for N = 9, 10. In the region of a binding energy below 1 MeV, the $2s_{1/2}$ orbital is below the $1d_{5/2}$ orbital. This fact is clearly observed as an abnormal ground-state spin-parity of ^{15}C (J^{π}=1/2^{+}). It is also observed as a strong contribution of the $2s_{1/2}$ orbital to the formation of a neutron halo in ^{11}Li, ^{11}Be and ^{14}Be (the mixing of $(2s_{1/2})^2$ and $(1p_{1/2})^2$ in the halo wave function). The lowering of the s orbitals is due to halo formation. A neutron halo is formed since the orbital with a low angular momentum gains energy by extending the wave function. This effect is largest in the s orbital and next in the p orbital. The effect for the p orbitals is also seen in Fig. 3.

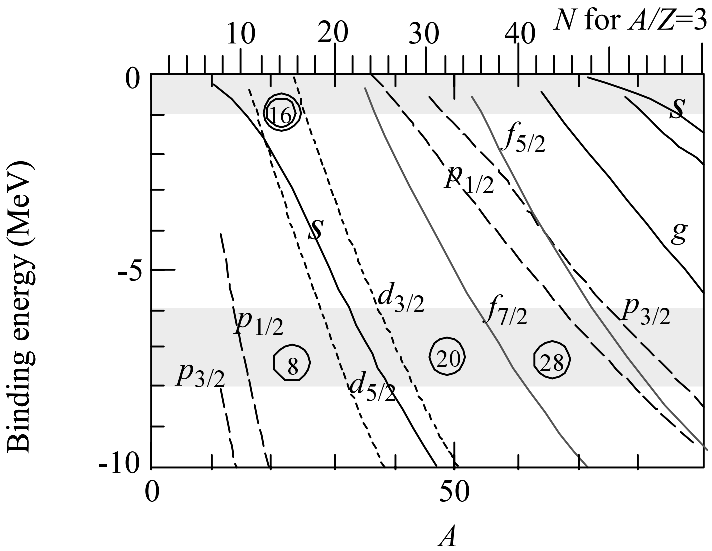

Fig. 3 Spectrum of single-neutron orbitals, obtained by the Woods-Saxon potential, for A/Z = 3 nuclei.

When the neutron number increases for a weakly bound system, strong mixing between $2s_{1/2}$ and $1d_{5/2}$ orbitals appears. Thus, the energy gap between these two orbitals and $1d_{3/2}$ become much larger. At weakly bound N = 16, the $2s_{1/2}$ and $1d_{5/2}$

orbitals are filled by neutrons leaving a large gap to the $1d_{3/2}$ orbital, as shown in Fig. 3. Thus, the mechanism that forms a neutron halo and makes the lowering of low-angular momentum orbitals, for weakly bound neutrons, is also essential for the appearance of the magic number N=16 near to the neutron drip-line. This mechanism may be common in nuclei near to the neutron drip-line. It therefore may destroy or produce other magic numbers in heavier elements, too.

4. Influence of the new magic number

Here, two aspects concerning the influence of the new magic numbers are pointed out. One is that the traditional nuclear shell model will be modified. A new modified shell model should explain the disappearance of magic numbers at neutron-rich N = 8 and 20, and the appearance of a magic number at N = 16 near to the neutron drip line. Another aspect is an influence on the *r*-process path. One of characteristics of the path is that the *r*-process goes through neutron magic numbers. Thus, if new magic numbers appear in the heavier neutron-rich region, such as near to N=82 and 126, the *r*-process path may be modified. Such a modification would solve any inconsistencies between calculations and observations for the *r*-process abundance [9].

5. Summary

In summary, a new magic number, N = 16, near to the neutron drip-line is introduced in this paper [10]. The new magic number has been surveyed by the neutron separation energies (S_n) and the interaction cross-sections (σ_I) for the neutron-rich *p-sd* and *sd* shell region. The neutron-number dependence of S_n shows clear breaks at N = 16 near to the neutron drip-line. The neutron-number dependence of σ_I shows a large increase in neutron-rich N = 15 nuclei, which shows that the purity of the $2s_{1/2}$ orbital is larger when the isospin number is larger in our analysis. These two facts indicate the appearance of a new magic number at N = 16 near to the drip-line. The origin of this new magic number may be due to neutron halo formation. The mechanism to form a new magic number may be common in nuclei near to the neutron drip-line. Other magic numbers in heavier elements may be produced. The new magic number may require modification of the traditional nuclear shell model and may change the possible *r*-process path.

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