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A Halo Driven New Magic Number $N=16$

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Recent studies of the structure of neutron-rich nuclei provides new insight into the shell structure in asymmetric nuclei. A new magic number $N=20$, which appears only in very neutron-rich nuclei, has been discovered. The evidences of this new magic numbers as well as the disappearance of magic numbers $N=8$ and 20 will be discussed. Possible reasons of the change of shell structures are also presented.

1. Introduction

Many new structures have been observed in neutron-rich nuclei in particular far from the stability line. Those studies show kaleidoscopic changes of shell contributions in ground states. Recent development of reaction models also provide tools to study the mixing of orbitals in neutron halo nuclei.

In this paper, I present the evidence of mixing of orbitals in halo nuclei in the next section. Then new anomalies of interaction cross sections are shown. In addition to these anomalies a systematic analysis of structure and binding energies has been made in neutron-rich p-sd shell nuclides. The strong evidence of a new magic number $N=16$ obtained from this analysis is presented in section 5. Some discussions on the break down of $N=8$ and 20 magic numbers are also summarized to give over all view of the change of shells.

2. Neutron Halos and a Mixing of Single-Particle Orbitals

A neutron halo is characterized by an extremely long tail of the density distribution and a decoupling of a halo neutron (or neutrons) from the other part of the nucleus usually called as the core. Experimentally it is identified by a large interaction- or a reaction-cross section and a narrow momentum distribution of the core fragment of the nucleus. [1] Lithium-11 and ^{11}Be are the most studied halo nuclei and are providing test grounds of nuclear models. Recently measurements of interaction cross sections (σ_I) have been extended to the neutron drip line up to Oxygen isotopes. As shown in the Fig. 1, established neutron halos as well as conjectured candidates are observed in isotopes of all the elements. Candidates of proton halos have also been reported.

Neutron halos are considered to appear in extremely weakly bound nuclei. It is also considered that the small angular momentum of the orbital is essential. Because of the

Fig. 1 Nuclei with halo structure are shown by the shaded square. Neutron radii of the density halos are found in nuclei of all elements near the drip line. Appearance of a new magic number $N=16$ is shown by the surrounding lines. Vanishing of $N=8$ and 20 magic numbers are also presented in the chart. The neutron drip-line are considered to be reached up to $Z=8$ and indicated by the dotted line.

A neutron in a higher orbital does not show this divergence. For two-neutron system outside the core, the rms radii diverges only when two neutron form $K=0$ and 1 system. Therefore extreme halos are formed in such low angular momentum neutrons.

centrifugal barrier, a neutron with a small orbital angular momentum extend the tail of the wave function much more than a neutron with a large orbital angular momentum. Conditions for the formation of halo has been studied by Jensen and Riisager. [2] They found an interesting behavior of loosely bound neutron(s). When one neutron is bound weakly to a core, an rms distribution of this neutron diverges to infinity as the separation energy goes to zero if it is in s- or p-orbital.

Fig. 2 Change of the contributions of s and d orbitals of neutron in p=sd shell. $2s_{1/2}$ orbital which usually appear $1d_{5/2}$ orbital plays an important role at the beginning of the shell and reappears after $1d_{5/2}$ shell again.

However the wave function of a halo neutron is not simple but shows substantial mixing as well as reordering of shell orbitals. For example, the order of $2s_{1/2}$ and $1p_{1/2}$ orbitals is reversed in ^{11}Be . The usually higher $2s_{1/2}$ orbital appears as the $1/2^+$ ground state and $1/2^-$ state appears as the first excited state. In ^{11}Li , the halo neutrons occupy $(1p_{1/2})^2$ and $(2s_{1/2})^2$ configurations with almost equal amplitudes. In p-sd shell, where protons are in p-shell and neutrons are in sd shell, the contribution of $2s_{1/2}$ and $1d_{5/2}$ orbitals show an interlacing in the ground states as shown in Fig. 2. At the beginning of the shell, $1s_{1/2}$ orbital plays an important role intermingled with $1p_{1/2}$ orbital. It is not expected in the "traditional" order of the orbitals. Although the $1d_{5/2}$ orbital plays an important role for the nuclei close to the stability line, strong mixing of $2s_{1/2}$ appears to be very important near the neutron drip line. The $2s_{1/2}$ orbital dominates for near drip line nuclei of N and O isotopes.

Fig. 3 Effective rms radii of point nucleon distribution deduced from interaction cross sections. Neutron halo easily identified with their large radii. Sudden increase of radii are observed from $N=14$ to 15 .

3. New Anomalies in Halo Nuclei.

The most visible character of a halo nucleus is its large size. The effective rms radii of nucleon distribution have been determined by measurements of interaction cross sections at high energy. [3] Figure 3 shows such experimentally determined effective matter radii. Neutron-halo nuclei are easily identified by the sudden increase of radii.

Density distributions of halo nuclei have usually been determined using a core+halo

model that is widely used by now. In this model the wave function of a nucleus is written as,

$$\Psi = \sum_i \psi_i^{core} \cdot \psi_i^{halo}, \quad (1)$$

where ψ_i^{core} is the wave function of the core and ψ_i^{halo} is the wave function of halo neutron(s), i denotes the states of different configurations. The ground state of the bare core nucleus and a few excited states of the bare core nucleus are considered as ψ_i^{core} . In ^{11}Be , for example, the ground state of $^{10}\text{Be}(0^+)$ and the first excited state (2^+ at 3.37 MeV) is used. The wave function of ^{11}Be is then written as,

$$\Psi(^{11}\text{Be}) = \alpha \cdot \psi^{core}(^{10}\text{Be}(0^+)) \cdot \psi^{halo}(2s_{1/2}) + \beta \cdot \psi^{core}(^{10}\text{Be}(2^+)) \cdot \psi^{halo}(2d_{5/2}). \quad (2)$$

The spectroscopic amplitudes α and β are used as parameters to fit the neutron separation energy, the σ_I , and the momentum distribution of the core fragment. The density distribution of the 2^+ core-excited state is assumed to be the same as 0^+ ground state. Such an analysis gives $\alpha \sim 0.8$ that is consistent with other determination from the analysis of the fragment momentum distribution [4] and from the analysis of the magnetic moment. [5]

However, new interaction cross section (σ_I) data of N, O, and F isotopes show

Fig. 4 Interaction cross sections of nuclei with $N=14$ and 15 . Large increases are observed for N, O, and F isotopes. The dotted line in each panel is the result of the core+neutron model assuming the pure $2s_{1/2}$ wave for the last neutron. The calculations do not reproduce the observed increases.

anomalies that can not be explained within the framework of such a model. [6] This situation is presented in Fig. 4. A large increase (about 10 %) of the σ_I is observed for each isotope when the 15th neutron is added. It shows a big contrast with that of Na isotopes where only

2% increase is observed. In the core+halo model, the largest cross section is obtained when the pure 2s-wave is used for the halo neutron. Even in such a case, the increase of the cross section from $N=14$ to 15 is way smaller in all the cases, as shown by the dotted line in each panel of the figure. The increase is well explained for Na isotopes instead. Therefore the interaction cross sections can not be explained by any configuration of halo wave function if we use the core+halo model described above.

Such an anomaly is also observed in ^{19}C nucleus. In this nucleus, one can find a reasonable mixture of wave functions that can explain the σ_I or the momentum distribution. However no consistent overlap can be seen in those two solutions. [7]

One of the possible solution to solve these anomalies is to change the size of the core. It has been reported that increase of core size by about 0.2 fm is enough to make everything consistent in ^{19}C and explain the increase of the interaction cross sections in ^{22}N , ^{23}O , and ^{24}F . [7] However the change of the core size is made rather arbitrary and has no theoretical base to it at this moment.

A possible reason of an enlarged core may be due to the effect of α -clustering in the core. It is known from AMD calculation that clustering may be enhanced in neutron rich nuclei. [8] In such a base, C and N isotopes may have large amplitude of 3α -clusters in neutron rich nuclei. Also 4α -clusters may be enhanced in neutron rich O and F nuclei. When $2s_{1/2}$ neutron is added in such a core, the relative distance of α 's may increase because $2s_{1/2}$ wave has large amplitude at the center of the core and Pauli exclusion principle may play a role and push α 's out. Rough estimate of such a model shows a possibility of an increase of core size. It might also appear as a low energy 0^+ excited state as breathing mode. However, such models are open problems for the future.

In any case, it is obvious we need a refined model of such a loosely bound nuclei.

4. Vanishing of Magic Numbers $N=8$ and $N=20$.

As we have seen in last sections, the shell structure of neutron-rich nuclei are radically changing. The most known case of such change is the disappearance of the magic number $N=20$ in neutron rich isotopes. It has been discovered by the measurement of masses and the isotope shifts of Na isotopes. [9] Recently, the $B(E2:2^+ \rightarrow 0^+)$ value of the transition between the first excited state and the ground state of ^{32}Mg has been determined by the Coulomb excitation. [10] The observed value is much larger than the value expected from the shell closure and thus shows the vanishing of $N=20$ magic numbers also in Mg. Recent Coulomb-excitation measurements of Si isotopes also show a weakening of the magic. [11]

The other interesting observation is a non-existence of "supposedly double-magic" nucleus ^{28}O . Many nuclear models predict ^{28}O be bound. However the recent measurement of Sakurai et al. showed that the possibility of the existence of bound ^{28}O is negligibly small. [12] It therefore indicates that the extra binding due to the magic number does not exist there. Talking about the drip line near ^{28}O , $N=16$ forms the straight drip line in C, N, and O. On the other hand, F shows the drip line that is beyond $N=20$. One more proton in F can hold 6

or probably more neutrons. It is also an interesting question why such a big jump of drip line occurs.

A disappearance of a magic number is also seen in $N=8$. In normal shell order, $1p$ -orbital is closed and forms $N=8$ magic number indicating a large gap in between p shell and sd shell. However sd -shell orbitals form the ground state of ^{11}Be as already shown in the previous section. A strong mixing of $(2s_{1/2})^2$ and $(1p_{1/2})^2$ in the halo neutrons of ^{11}Li is also evident. Recently, sophisticated measurement has been reported in ^{12}Be by Navin et al. [13] They could separate the contribution of $l=0$ and $l=1$ component in the ground state from the measurement of ^{11}Be fragment in coincidence with the gamma-ray transition from the first excited state of ^{11}Be . They concluded that $(2s_{1/2})^2$ and $(1p_{1/2})^2$ are almost equally mixed in the ground state of ^{12}Be . Therefore, it is shown that the magic number $N=8$ disappears for neutron rich isotopes. A similar situation as ^{28}O also exist in this case. A "supposedly double-magic" nucleus ^{10}He is also not bound. It is observed only as resonance state. [14] In addition, Li isotope extend beyond $N=8$ and make the drip line at $N=10$.

So far only two "supposedly doubly magic" region (^{10}He , ^{28}O) have been studied near the neutron drip line. Both of them (that means in all of the known such regions) show abnormal, but similar to each other, behavior and the neutron magics vanish. Are all magic numbers vanish near the drip line and shell structure disappears? Or different ordering appears? It is an extremely important question.

5. A New Magic Number $N=16$.

One of the best way to identify a magic number is a systematics of neutron separation energies (S_n). We show a neutron (N) number dependence of experimentally observed S_n [2] for nuclei with odd N and even Z (odd N and odd Z) in Fig. 5 (a) (Fig. 5 (b)), respectively. In Fig. 5, a magic number appears as a decrease of S_n along with an increase of N . The traditional magic numbers ($N=8, 20$) are clearly seen near the stable nuclei as breaks in the small T_z

Fig. 5 The single neutron separation energies for nuclides of different isospin. Downward kinks appears at $N=16$ for nuclides with isospin larger than 3.

lines. However, the break at $N=8$ ($N=20$) disappears at $T_z=3/2$ ($T_z=4$), 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 $T_Z \geq 3$, as clearly shown in Fig. 5, which indicates the creation of a new magic number in $N=16$ near to the neutron drip-line. [6]

Fig. 6 Neutron number dependence of the interaction cross section with C target at around 900A MeV beam.

$N=15$. Figure 7 (a) shows the S-factor of the $2s_{1/2}$ orbital in $N=15$ nuclei determined by (d, p) reactions. [15] For nuclei near the stability line the S-factor ranges from 0.3 to 0.8 indicating the mixing of other orbitals. However the S-factor increases as the proton number decreases. This is a smooth connection to the result of analysis of interaction cross sections that suggests a high-purity of s-wave. These data therefore are consistent with the appearance of a new magic number $N=16$.

In Fig. 6, a neutron (N) number dependence of experimentally observed σ_I for N to Na isotopes was shown. A steep increase of σ_I from $N=14$ to $N=15$ for N to F isotopes were observed. On the other hand, for Ne to Mg isotopes, no steep increase of σ_I was observed. It is noted that a clear change occurs at $T_Z=3$, which suggests a correlation to the new magic number $N=16$, as shown in S_n . Although it was not fully understood, core+halo model analysis suggested that $2s_{1/2}$ orbital become pure in N, O, and F isotopes at

Fig. 7 Other evidences of magic number $N=16$. (a) The S factor of $2s_{1/2}$ become more pure when Z become smaller. (b) The excitation energy of the first excited state increases as large as 4 MeV. It suggest that the nuclei here are spherical.

Recently the 2^+ excited states were studied for O and Ne isotopes. [16] Excitation energy of first 2^+ state in $N=16$ isotopes are much higher than that of $N=12$ as seen in Fig. 7b. Therefore it also indicates the magicity of $N=16$ in O and Ne isotopes.

Theoretically Beiner et al. predicted in 1975 a new magic number $N=16$ exactly in the presently discussed region of the nuclear chart. [17] They calculated the broadening of the occupation number distribution, $\sigma_n(N)$,

$$\sigma_n(N) = \left(\langle \hat{N}^2 \rangle - \langle \hat{N} \rangle^2 \right)^{1/2} = \sqrt{2 \sum_v (2j_v + 1) v_v^2 (1 - v_v^2)} \quad (3)$$

using the energy-density formalism. Where $\hat{N}$ is the neutron number operator and v_v is the occupation number of the orbital v . $\sigma_n(N)$ become 0 at $N=16$ for C, N, and O. (see Fig. 8) It indicates that $N=16$ there is a good magic number and the nuclei there are spherical. Recent shell model calculations by Otsuka et al. also suggest that the gap between $2s_{1/2}$ and $d_{3/2}$ become as large as 5 MeV at $N=16$. [18]

Fig. 8 The broadening factor σ_n of the neutron occupation number for C, N, and O isotopes. σ_n become zero at $N=16$ and indicates the spherical magic number at this number.

In all it is strongly indicated that a new magic number $N=16$ appears for neutron rich isotopes of C, N, O, F and may be of Ne. The appearance of the new magic number at $N=16$ near to the neutron drip-line and the disappearance of the magic number at neutron-rich $N=20$ provide an easier understanding of the drip line of O and F isotopes: the non-existence of bound “double magic” nuclei ^{28}O and the extension of the neutron drip line of F isotopes beyond $N=20$. A large shell gap between $2s_{1/2}$ and $1d_{3/2}$ at neutron-rich $N=16$ brings the $1d_{3/2}$ orbital higher up and,

thus, this orbital become unbound in O isotopes (^{28}O unbound). The $1d_{3/2}$ orbital may thus be mixed with other higher orbitals. When this orbital is occupied, the many mixed higher orbitals may be close together and, thus, the drip line of F isotopes is extended.

One of the origin of this new magic number may be due to neutron halo formation. Figure 9 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 an effect of neutron excess. Normal shell gaps $N=8, 20, 28$ are seen in the region of 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 ($J^\pi=1/2^+$). 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 ^{12}Be (the mixing of $(2s_{1/2})^2$ and $(1p_{1/2})^2$ in the halo wave function).

Fig. 9 Single particle orbitals in Woods-Saxon potential for $A/Z=3$ nuclei. Potential parameter from Bohr mottelson's book [19] has been used. Low angular momentum orbitals become lower in energy due to the halo formation effect.

The lowering of the s orbitals is due to halo formation. The 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. 9.

The diffuseness parameter of the Woods-Saxon potential was fixed to a normally used value in calculating Fig. 9. [19] The lowering of low-angular momentum orbitals is more pronounced for a potential with a larger diffuseness, which is due to the self-consistent nature of the density distribution and the potential. Therefore, the lowering of the s orbital is expected to be more

pronounced in reality.

When a neutron number increases for a weakly bound system, a strong mixing between $2s_{1/2}$ and $1d_{5/2}$ orbitals appear. 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. 9.

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. Such effects are expected to affect the ordering of orbitals near $N=28$ and 50.

In addition to the weak binding effect and deformation that is responsible for the disappearance of $N=20$ magic number, several other origins of the change of shell may come into play. They are:

1. Changes of the shape of the potential. It includes the change of the surface diffuseness and the tail, and the decoupling of the proton and the neutron density

distributions.

2. Changes of l - s coupling. It includes the change of the coupling strength as well the change due to the change of the shape of the potential.
3. The coupling between a state near the threshold and continuum is also a very important effect.
4. Various types of clustering may occur in neutron rich nuclei due to the additional neutron cloud.

Studies of these effects are some of the most important tasks at the RI Beam facilities.

6. Conclusion

In conclusion, I have shown the various cases of the change of the shell structure in p and sd shell neutron-rich nuclei. In addition to the vanishing of magic numbers $N=8$ and 20, a new magic number $N=16$ has been discovered recently. It is also suggested that the magic numbers may change in heavier nuclei. Future experiments for heavier nuclei are awaited.

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