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Recent radioactive ion beam program at RIKEN and related topics

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Abstract. Recent experimental programs at RIKEN concerning RI beams are reviewed. RIKEN has the ring cyclotron (RRC) with high intense heavy-ion beams and large acceptance fragment separator, RIPS. The complex can provide high intense RI-beams. By using the high intense RI-beams, a variety of experiments have been done. Recently, nuclear structure for unstable nuclei has been paid much attention. In special, disappearance and appearance of magic numbers are discussed experimentally and theoretically. Thus, in this review, related experiments concerning disappearance and appearance of magic numbers are described. Finally, future project in RIKEN, RI-beam factory, is introduced briefly.

Keywords. RIKEN; radioactive ion beams; magic numbers.

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1. Introduction

In RIKEN, there are several heavy ion accelerators. Main accelerator is the RIKEN ring cyclotron (RRC) with $K = 540$, that has been operated from 1986. The RRC has two injectors; one is heavy ion linear accelerator that has been operated from 1981, and the other is AVF cyclotron with $K = 70$, that has been operated from 1989. The RRC can provide heavy ion beam to seven experimental areas; E1 to E7. Fragment separator, RIPS, is located at E6. RIPS has large momentum and angular acceptances, and also large rigidity (5.76 Tm) [1]. Thus, RIPS can produce high-intense and very neutron-rich RI-beams. RIPS has a unique device, so called swinger magnets upstream of the production targets. By the magnets, primary beam can be bent up to 10 degree, that is essential for the production of polarized RI beams.

Recent progress of RI beam technique allows to understand nuclear structure of unstable nuclei. The structure for unstable nuclei is very different from that for stable ones, for example existence of a skin and a halo [2]. Recently, magicity for unstable nuclei has been paid much attention. Several experiments suggest disappearance of magic numbers of $N = 8$ [3] and $N = 20$ [4] at very neutron rich region, and recently, $N = 16$ magic number has been found near the neutron drip line [5].

In this review, recent experiments with RI-beams at RIKEN is reviewed. In special, experiments related to the magicity of unstable nuclei has been focussed.

2. Recent RI beam program at RIKEN

One of important program at RIKEN is new isotope search for neutron rich region. RIPS has some advantages for the subjects since it has large acceptances and large rigidity. Also, RRC can provide high intense primary beams, for example 70 pnA for ^{40}Ar. Recently, ^{28}O has been searched and particle instability of ^{28}O and particle stability of ^{31}F have been shown. [6].

Gamma-ray detection is another main subject in RIKEN. In RIKEN, using large solid-angle NaI detectors, Coulomb excitation and/or nuclear excitation have been investigated for neutron rich nuclei. One of the pioneer work was done for ^{32}Mg. In the experiment, Coulomb excitation of ^{32}Mg to its 2^+ excited state was measured and its $B(E2)$ value of 454 ± 78 e^{2}fm^2 was extracted. The large value suggests the vanishing of the $N = 20$ shell gap [4].

Recently, by using similar set up, Coulomb excitation of ^{12}Be has been studied. The strong gamma-ray transition from the state at $E_x = 2.68$ MeV following E1 Coulomb excitation was observed for the lead target, leading to an assignment of $J^\pi = 1^-$ for the excited state. The large $B(E1)$ value of 0.051 e^2 fm^2 for the 2.68 MeV state was deduced. The lowering of the intruder 1^- state accompanied with the large E1 strength represents the characteristic feature of degenerate $1p_{1/2}$ and $2s_{1/2}$ states, thus indicating the melting of $N = 8$ magicity in ^{12}Be [3].

Very recently, two-step fragmentation reaction have been applied to gamma ray detection [7]. Two step fragmentation has some advantages compared with one step fragmentation. In the two step, one can use thick production target and production cross-section is large, thus as the total number of observed gamma-rays are larger than those by one step since, in the one step process, primary beam intensity and the target thickness are limited to avoid accidental coincidence. The two step fragment reaction have been applied to ^{34}Mg. ^{34}Mg has been produced by ^{36}Si beams that has been produced from ^{40}Ar primary beam. Doppler-corrected gamma-ray spectra associated with ^{34}Mg is shown in figure 1a. According to the systematics of the gamma-ray intensities for fragmentation reactions the strongest line at 660 keV can be assigned to the 2_1^+ to 0_{gs}^+ transition, resulting in $E(2_1^+) = 660$ keV for ^{34}Mg. As for the second strongest line in the ^{34}Mg spectrum, the assignment is less certain. However, it is plausible that the line corresponds to the 4_1^+ to 2_1^+ transition by again referring to the systematics of the fragmentation reactions. With this assignment, the value of $E(4_1^+)$ is 2120 keV, leading to the $E(4_1^+)/E(2_1^+)$ ratio about 3.2, which suggests the large deformation of ^{34}Mg. The ratio is also close to recent predictions by variational shell model calculations [8].

One of major subjects in RIKEN is measurements of magnetic and quadrupole moments for unstable nuclei by using polarized RI beams. The polarization degree is not so high, roughly less than 10%, but is enough for the measurements of the moments by so called β-NMR methods. Recent work was done for ^{17}C, which has a small neutron separation energy and is a potential neutron halo candidate. However, its nuclear structure is not known well, in special, its spin-parity is not known. Magnetic moments are very sensitive to spin-parity, for example, if its spin-parity is 1/2$^+$, magnetic moments is -3.83, on the other hand, if its spin parity is 3/2$^+$, it is -0.76.

Results of measurement was 0.5054, which was close to 0.76 [9]. Thus, 3/2$^+$ was concluded by the measurement. More realistic shell model calculations are closer to the observed value, thus, 1/2$^+$ is definitely rejected. The spin-parity suggests the dominance of $1d_{5/2}$ for the valence neutron, which is suggested by other experimental observable [10].

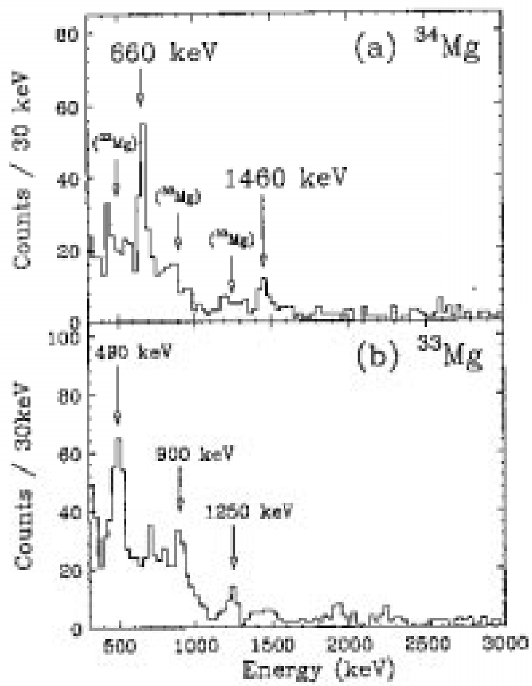

Figure 1. Doppler-corrected gamma-ray spectra associated with ^{34}Mg (**a**) and ^{33}Mg (**b**). In the spectrum of ^{34}Mg (a), two sharp peaks can be seen at energies of 660 keV and 1460 keV. Three peaks associated with ^{33}Mg are seen in (a) due to the limited mass resolution for reaction products.

In RIPS, there is a large acceptance C-type magnet. One of the advantages of the magnet is a large acceptance of neutrons. Using the magnet, elastic and inelastic scatterings for light unstable nuclei, and Coulomb dissociation for light neutron rich nuclei have been studied. Recently, Coulomb dissociation for ^{19}C has been studied using the magnet [11]. ^{19}C has been known as one neutron halo nuclei, but its halo structure is not known well. A large E1 strength has been observed at low excitation energies, which suggests a ^{19}C ground state strength with a dominant d-wave valence neutron. Furthermore, an analysis of the angular distribution of ^{19}C plus neutron center of mass has led to a determination of the neutron separation energy of ^{19}C to be 530 $\pm$ 130 keV, that is much larger than adopted value (160 keV).

3. Related topics

3.1 *Measurements of interaction cross sections*

After the pioneering work at LBL [12], the interaction cross-sections ($\sigma_{\rm I}$) have been extensively measured for light unstable nuclei $(A \leq 30)$. Measurements of $\sigma_{\rm I}$ at relativistic

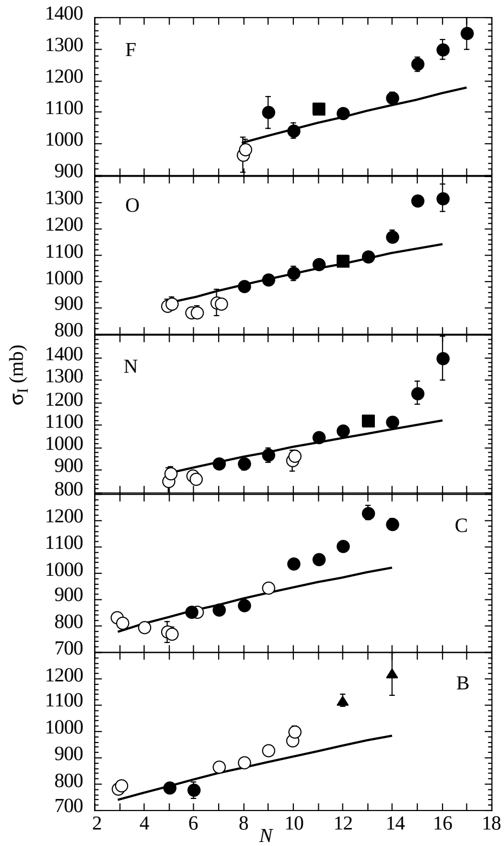

Figure 2. Interaction cross sections ($\sigma_{\rm I}$) for boron, carbon, nitrogen, oxygen and fluorine isotopes on carbon targets. The filled points are data obtained in GSI. The open points are data from previous studies at LBL.

energies (around $1A$ GeV) have allowed one to deduce the effective nuclear matter radii using Glauber model calculations.

$\sigma_{\rm I}$ has been measured by a transmission-type experiment [12]. The cross section was calculated by the equation

$$\sigma_{\rm I} = \frac{1}{N_{\rm t}} \log\left(\frac{\gamma_0}{\gamma}\right), \tag{1}$$

where γ is the ratio of the number of non-interacting nuclei to the number of incoming nuclei for a target-in run, and γ_0 is the same ratio for an empty-target run. The number of target nuclei per cm^2 is written as $N_{\rm t}$. Particle identification is necessary at the upstream and downstream of the reaction target.

The measured $\sigma_{\rm I}$ values are shown as a function of the neutron number (N) for boron, carbon, nitrogen, oxygen and fluorine isotopes in figure 2 [13]. The observed $\sigma_{\rm I}$ increased monotonically with N. It is noted that the rate of increase with N changes at $N = 15$. The solid lines in figure 2 show the $\sigma_{\rm I}$ values calculated using the equation

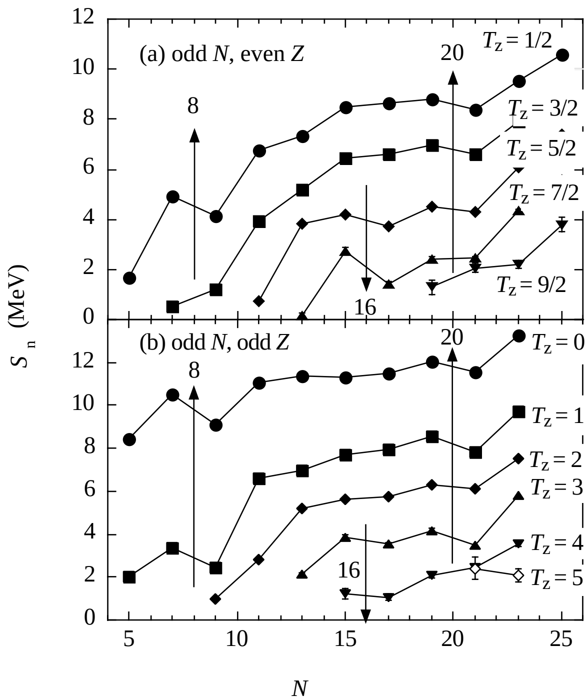

Figure 3. Neutron (N) number dependence for experimentally observed neutron separation energies (S_n) for nuclei with odd N and even Z (**a**) and odd N and odd Z (**b**), respectively.

$$\sigma_{\rm I} = \pi\,(R_{\rm I}(^{12}{\rm C}) + r_0 A^{\frac{1}{3}})^2, \qquad (2)$$

where $R_{\rm I}(^{12}{\rm C})$ is the interaction radius of ^{12}C (2.61 fm) and r_0 is selected to reproduce $\sigma_{\rm I}$ for ^{12}C. In the neutron-rich side, the observed rate of increase is much larger than that calculated by eq. (2). This increase in the rate could indicate a thick neutron skin on the neutron-rich side. The observed $\sigma_{\rm I}$ for ^{19}C is much larger than those of its neighbors, which supports a halo structure of this nucleus.

3.2 *New magic number, $N = 16$, near the neutron drip-line*

Recently, the neutron separation energies (S_n) and the $\sigma_{\rm I}$ for neutron-rich p-sd and sd shell region have been surveyed in order to search for a new magic number [5]. A neutron (N) number dependence of experimentally observed S_n for nuclei with odd N and even Z (odd N and odd Z) is shown in figure 3. The N-number dependence of S_n shows clear breaks at $N = 16$ near the neutron drip-line, which shows the creation of a new magic number. The N-number dependence of $\sigma_{\rm I}$ shows a large increase of $\sigma_{\rm I}$ for neutron-rich $N = 15$, which supports the new magic number, as follows. As can be seen in figure 4, the

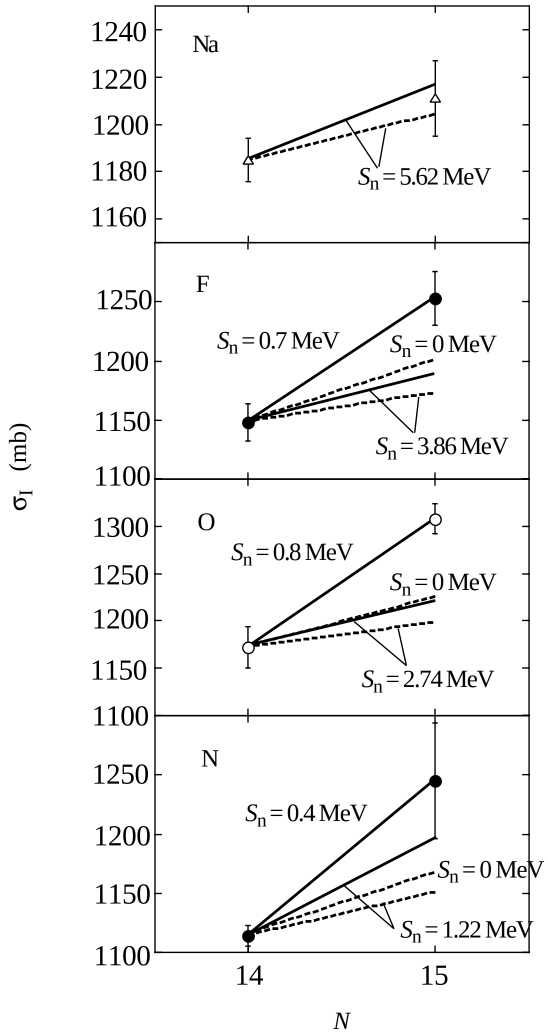

Figure 4. $\sigma_{\rm I}$ for nuclei with $N = 14, 15$ on C targets. The solid (dashed) lines show the increase of $\sigma_{\rm I}$ calculated by Glauber model calculations for few-body systems assuming a pure $2s_{1/2}$ $(1d_{5/2})$ orbital for the valence neutron with given neutron separation energies (S_n), respectively. The unit of S_n is given by MeV.

observed $\sigma_{\rm I}$ can be reproduced only using the $2s_{1/2}$ orbital. For the case of the $1d_{5/2}$ orbital, we can not reproduce the observed $\sigma_{\rm I}$, even if we use $S_n = 0$ MeV, as shown by the dashed lines in figure 4. Thus, we conclude a dominance of the $2s_{1/2}$ orbital for the valence neutron in ^{22}N, ^{23}O and ^{25}F. On the other hand, the increase of $\sigma_{\rm I}$ from ^{25}Na to ^{26}Na can be explained by mixing the $2s_{1/2}$ and $1d_{5/2}$ orbitals, as shown in figure 4. We could not perform a meaningful analysis for Ne and Mg isotopes because of the rela-

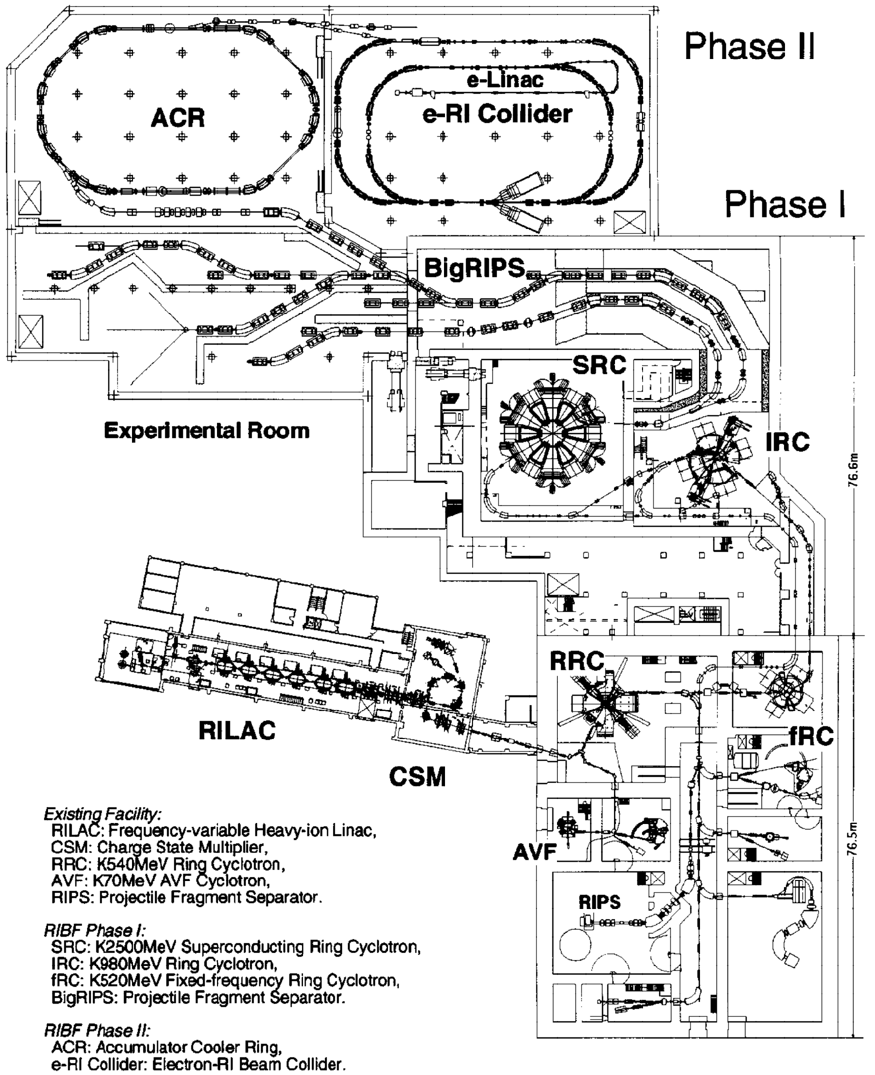

Figure 5. The layout of the RIKEN RI beam factory (RIBF). The RIBF is extraction of the existing heavy-ion accelerator facility.

tively large error bars for $\sigma_{\rm I}$. However, the rates for the increase of $\sigma_{\rm I}$ for the isotopes are also similar to those for the Na-isotopes. Thus, we also conclude that a valence neutron for ^{25}Ne and ^{27}Mg is a mixing of the $2s_{1/2}$ and $1d_{5/2}$ orbitals. Thus, the purity of $2s_{1/2}$ drastically increases near to the drip-line for $N = 15$ nuclei. 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 drip-line. The origin of this new magic number may be due to neutron halo formation. At weakly bound $N = 16$, the $2s_{1/2}$ and $1d_{5/2}$ orbitals are filled by neutrons leaving a large gap in the $1d_{3/2}$ orbital.

4. Introduction of RI beam factory project at RIKEN

The RI Beam Factory is being constructed at RIKEN, which is a project to construct a set of equipment which includes a superconducting ring cyclotron (SRC) and experimental storage rings (MUSES). Its schematical drawing is shown in figure 5. Heavy ions are to be accelerated to energies of up to 350*A* MeV for light nuclei and 150*A* MeV for the heaviest nuclei by the SRC and up to 1000*A* MeV in the MUSES. RI beams are to be supplied as secondary beams. Electrons, stable nuclei, and highly charged ions in addition to radioactive nuclei can be stored in the storage rings. The MUSES provide various collision methods, such as colliding and internal target methods. The heavy-ion beams obtained from SRC will be converted into RI beams by a separator complex, called 'big RIPS'. Big RIPS consists of two fragment separators, one of which is comprised of superconducting quarupole magnets with large acceptances.

Construction of SRC and the part of big RIPS will be completed at the end of 2003. Thus, the first beam from the cyclotron will be delivered in 2004. The construction of MUSES will be started at 2002 and will be finished in 2005. The first electron-scattering experiment on unstable nuclei is scheduled for 2009.

5. Summary

Some recent experimental programs with RI beams at RIKEN are reviewed. Recent topics on a new isotope search, gamma-ray detection for RI beams, magnetic moment measurements of RI beams and Coulomb dissociation measurements are presented. These experimental results revealed that RIPS is a powerful tool to search nuclear structure of unstable nuclei.

Measurements of the interaction cross sections ($\sigma_{\rm I}$) have been made by a transmission method at relativistic energies. At the FRS in GSI, recent experiments have been performed for mainly light nuclei up to F.

Recently, a new magic number, $N = 16$, near the neutron drip line is shown by the neutron-number dependence of the neutron separation energies. The $\sigma_{\rm I}$ values for $N = 15$ isotopes (^{22}N to ^{24}F) are larger than those of $N = 14$ nuclei, which also supports the magic number.

RI beam factory (RIBF) project in RIKEN is also introduced. RIBF consists of superconducting ring cyclotron (SRC) and multi uses storage rings (MUSES). By the complex, high intense high energy RI beams will be available and a lot of interesting experiments, such as electron scattering with RI beams, will be performed.

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