Examining exotic structure of proton-rich nucleus $^{23}\text{Al}$

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The longitudinal momentum distribution ($P_{||}$) of fragments after one-proton removal from $^{23}\text{Al}$ and reaction cross sections ($\sigma_R$) for $^{23,24}\text{Al}$ on carbon target at 74 A MeV have been measured. The $^{23,24}\text{Al}$ ions were produced through projectile fragmentation of 135 A MeV $^{28}\text{Si}$ primary beam using RIPS fragment separator at RIKEN. $P_{||}$ is measured by a direct time-of-flight (TOF) technique, while $\sigma_R$ is determined using a transmission method. An enhancement in $\sigma_R$ is observed for $^{23}\text{Al}$ compared with $^{24}\text{Al}$. The $P_{||}$ for $^{23}\text{Mg}$ fragments from $^{23}\text{Al}$ breakup has been obtained for the first time. FWHM of the distributions has been determined to be $232\pm28$ MeV/c. The experimental data are discussed by using Few-Body Glauber model. Analysis of $P_{||}$ demonstrates a dominant $d$-wave configuration for the valence proton in ground state of $^{23}\text{Al}$, indicating that $^{23}\text{Al}$ is not a proton halo nucleus.

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Since the pioneering measurements of interaction cross sections ($\sigma_I$) and observation of a remarkably large $\sigma_I$ for $^{11}\text{Li}$ $^{[1,2]}$, exotic structures like neutron halo or skin in light neutron-rich nuclei have been found. Experimental measurements of reaction cross section ($\sigma_R$), fragment momentum distribution ($P_{||}$) after one or two nucleons removal, quadrupole moment and Coulomb dissociation have been demonstrated to be very effective methods to investigate nuclear halo structure. The neutron skin or halo nuclei $^{6,8}\text{He}$, $^{11}\text{Li}$, $^{11}\text{Be}$, $^{13}\text{C}$ etc. $^{[1,2,3,4,5,6,7]}$, have been identified by these experimental methods. Due to Coulomb barrier, identification of a proton halo is more difficult compared to a neutron halo. The quadrupole moment, $P_{||}$ and $\sigma_R$ data indicate a proton halo in $^{8}\text{B}$ $^{[8,9,10,11,12]}$, whereas no enhancement is observed in the measured $\sigma_I$ at relativistic energies $^{[8]}$. The proton halo in $^{26}\text{P}$ and $^{27}\text{S}$ has been predicted theoretically $^{[14,15]}$. Measurements of $P_{||}$ have shown a proton halo character in $^{26,27,28}\text{P}$ $^{[16]}$.

Proton-rich nucleus $^{23}\text{Al}$ has a very small separation energy $(S_p = 0.125$ MeV) $^{[17]}$ and is a possible candidate of proton halo. An enhanced $\sigma_R$ for $^{23}\text{Al}$ has been observed in a previous experiment $^{[18,19]}$. To reproduce the $\sigma_R$ for $^{23}\text{Al}$ within framework of Glauber model, a dominating $2s_{1/2}$ component for the valence proton is shown $^{[18]}$. A long tail in proton density distribution has been extracted for $^{23}\text{Al}$ which indicated halo structure. The spin and parity $(J^p)$ for ground state of $^{23}\text{Al}$ has been deduced to be $5/2^+$ in a recent measurement of magnetic moment $^{[20]}$. This result favors a $d$-wave configuration for the valence proton in $^{23}\text{Al}$. But it does not eliminate the possibility of a $s$-wave valence proton if its $^{22}\text{Mg}$ core is in excited state. Therefore it will be very important to determine configuration of the valence proton for $^{23}\text{Al}$. As we know, $P_{||}$ of the fragment carries structure information of the projectile. However, there are no such experimental data for $^{23}\text{Al}$ up to now. In this paper we will report simultaneously measurements of $\sigma_R$ and $P_{||}$ for $^{23}\text{Al}$ and also $\sigma_R$ for $^{24}\text{Al}$.

The experiment was performed at the RIKen Projectile fragment Separator (RIPS) in RIKEN Ring Cyclotron Facility. The experimental setup is shown in Fig. 1. Secondary beams were generated by fragmentation reaction of 135 A MeV $^{28}\text{Si}$ primary beam on a $^{9}\text{Be}$ production target in F0 chamber. In the dispersive focus plane F1, an Al wedge-shaped degrader (central thickness: 583.1 mg/cm², angle: 6 mrad) was installed. A delay-line readout Parallel Plate Avalanche Counter (PPAC) was placed to measure the beam position. Then the secondary beam was directed onto the achromatic focus F2. Two delay-line readout PPACs were installed to determine the beam position and angle. An ion chamber (200$\phi \times 780$mm) was used to measure energy loss ($\Delta E$) of the secondary beams $^{[21]}$. An ultra-fast plastic scintillator (0.5 mm thick) was placed before a carbon reaction target (377 mg/cm² thick) to measure time-of-flight (TOF) from the

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PPAC at F1. The particle identification before the reaction target was done by means of $Bp - \Delta E - \text{TOF}$ method.

After the reaction target, a quadrupole triplet was used to transport and focus the beam onto F3 (∼6 m from F2). Two delay-line readout PPACs were used to monitor the beam size and emittance angle. Another plastic scintillator (1.5 mm thick) gave a stop signal of the TOF from F2 to F3. Two delay-line readout PPACs were used to monitor the beam size and emittance angle. Another plastic scintillator (1.5 mm thick) gave a stop signal of the TOF from F2 to F3. A smaller ion chamber ($90 \phi \times 650 \text{mm}$) was used to measure energy loss ($\Delta E$) of the beam. Total energy ($E$) was measured by a NaI(Tl) detector. The particles were identified by TOF−$\Delta E$−$E$ method. An example of typical particle identification spectra at F3 for the fragment from $^{23}\text{Al}$ breakup is shown in Fig. 2. In this spectrum, fragments with different nuclear charge were already subtracted by TOF and $\Delta E$ method.

Under assumption of a sudden valence-nucleon removal, the momentum distribution of fragments can be used to describe that of the valence proton. The $P_{//}$ of fragments from breakup reactions was determined from the TOF between the two plastic scintillators installed at F2 and F3. Position information measured by the PPAC at F1 was used to derive incident momentum of the beam.

The momentum of fragment relative to the incident projectile in laboratory frame was transformed into that in the projectile rest frame using Lorentz transformation.

In order to estimate and subtract reactions of the projectile in material other than the carbon target, measurements without the reaction target were also performed and the beam energy was reduced by an amount corresponding to the energy loss in the target. For one-proton removal reactions of $^{23}\text{Al}$, this background was carefully reconstructed and subtracted based on ratio of fragments to unreacted projectile identified in the target-out measurement and also broadening effect of the carbon target on $P_{//}$. The obtained momentum distribution of $^{22}\text{Mg}$ fragments from $^{23}\text{Al}$ breakup in the carbon target at 74.4 MeV is shown in Fig. 3. We normalized experimental counts to the measured one-proton removal cross section ($\sigma_{-1p}$) so that $\sum N(p_i)\Delta p_{i||}$ equals $\sigma_{-1p}$. A Gaussian function was used to fit the distributions. The full width at half maximum (FWHM) was determined to be 232±28 MeV/c after unfolding the Gaussian-shaped system resolution (41 MeV/c). The FWHM is consistent with Goldhaber model’s prediction (FWHM=212 MeV/c with $\sigma_0 = 90$ MeV/c) within the error bar [22]. Since magnetic fields of the quadruples between F2 and F3 were optimized for the projectile in the measurement, momentum dependence of transmission from F2 to F3 for fragments was simulated by the code MOCADI [23]. The effect of transmission on the width of $P_{//}$ distribution was found to be negligible which is similar with the conclusion for neutron-rich nuclei [24, 25]. Using the estimated transmission value, the one-proton removal cross sections for $^{23}\text{Al}$ was obtained to be 63±9 mb.

Reaction cross section is determined using the transmission method:

$$\sigma_R = \frac{1}{t} \ln \left( \frac{\gamma_0}{\gamma} \right)$$  \hspace{1cm} (1)

where $\gamma$ and $\gamma_0$ denote ratio of unreacted outgoing and incident projectiles for target-in and target-out cases, respectively; $t$ thickness of the reaction target, i.e., number of particle per unit area.
The $\sigma_R$ of $^{23,24}$Al at 74 A MeV were obtained to be 1609±79 mb and 1527±60 mb, respectively. The errors include statistical and systematic uncertainties. Probability of inelastic scattering reaction was estimated to be very small (< 1%), e.g., the inelastic cross section is only around 11 mb for $^{23}$Al which is much smaller than the error of $\sigma_R$.

Results of previous and current experiments are shown in Fig. 4. Since the energy is different in two experiments, the previous $\sigma_R$ data at ~ 30 A MeV [18] were scaled to the present energy (74 A MeV) using a phenomenological formula [26]. First the radius parameter ($r_0$) in this formula was adjusted to reproduce the $\sigma_R$ at ~ 30 A MeV, then the same $r_0$ was used to calculate the $\sigma_R$ at 74 A MeV. As shown in Fig. 4 the $\sigma_R$ of $^{23,24}$Al from present and previous experiments are in good agreement. And we observed a small enhancement in $\sigma_R$ for $^{23}$Al in our data again.

To interpret the measured reaction cross sections and momentum distributions, we performed a Few-Body Glauber model (FBGM) analysis for $P_{jj}$ of $^{23}$Al → $^{22}$Mg processes and $\sigma_R$ of $^{23,24}$Al [27, 28, 29]. In this model, a core plus proton structure is assumed for the projectile. The total wavefunction of the nucleus is expressed as

$$\Psi = \sum_{ij} \psi_{\text{core}} \phi_{ij},$$

where $\psi_{\text{core}}$ and $\phi_{ij}$ are wavefunctions of the core and valence proton; $i,j$ denote different configurations for the core nucleus and valence proton, respectively. For the core, harmonic oscillator (HO) functions were used for the density distributions. The wavefunction of the valence proton was calculated by solving the eigenvalue problem in a Woods-Saxon potential. The separation energy of the last proton is reproduced by adjusting the potential depth. In the calculation, the diffuseness and radius parameter were chosen to be 0.67 fm and 1.27 fm, respectively [24].

In the recent $g$-factor measurement using a $\beta$-NMR method, the spin and parity for ground state of $^{23}$Al is shown to be $5/2^+$. It gives a strong restriction on the possible structure of this nucleus. Assuming $^{22}$Mg+$p$ structure, three most probable configurations for $J^T = 5/2^+$ of $^{23}$Al are: $0^+ \otimes 1d_{5/2}$, $2^+ \otimes 1d_{5/2}$ and $2^+ \otimes 2s_{1/2}$ [20]. The $s$-wave configuration is therefore possible for the core in the excited state.

The momentum distributions for the valence proton in $s$ or $d$-wave configuration are calculated by using FBGM. In this calculation, the parameters $a$ and $\sigma_{NN}$ in the profile function $\Gamma(b) = \frac{1}{4\pi a^2} \sigma_{NN} \exp(-\frac{b}{2a})$ ($b$ is the impact parameter) are taken from Ref. [28]. The range parameter $\beta$ is calculated by the formula which is determined by fitting the $\sigma_R$ of $^{12}$C + $^{12}$C from low to relativistic energies [30]. $\beta$ is 0.35 fm at 74 A MeV. To fix the core size, the width parameters in the HO density distribution of $^{22}$Mg were adjusted to reproduce the experimental $\sigma_I$ data at around 1 A GeV [31]. The extracted effective root-mean-square matter radius ($R_{\text{rms}} \equiv < r^2 >^{1/2}$) for $^{22}$Mg is 2.89 ± 0.09 fm. To see the separation energy dependence, the FWHM of $P_{jj}$ is determined assuming an arbitrary separation energy in calculation of the wavefunction for the valence proton in $^{23}$Al and shown in Fig. 5. If we adopt a larger radius of $R_{\text{rms}} = 3.6$ fm for $^{22}$Mg to see the core size effect on $P_{jj}$, we obtained solid and open squares of FWHM in Fig. 5. The one proton separation energies for $^{22}$Mg in the ground and excited ($J^T = 2^+$, $E_x = 1.25$ MeV) states are taken as 0.125 MeV and 1.375 MeV ($E_x + 0.125$ MeV). Those two values are marked by two arrows in Fig. 5. In this figure, we can see that the width for the $s$ and $d$-wave are obviously separated. The width for the $s$-wave is much lower than the experimental data, while that of the $d$-wave is close to the experimental FWHM. With the increase of...
From above discussions of $P_{1/2}$, the valence proton in $^{23}$Al is determined to be in the $d$-wave configuration, which is used in the following calculations. In the calculation of $\sigma_R$ for $^{23}$Al using the FBGM, at first $R_{\text{rms}} = 2.89 \pm 0.09$ fm is used for its $^{22}$Mg core by reproducing the $\sigma_I$ data as described above. But the calculated $\sigma_R$ is much lower than the obtained $\sigma_R$ data. One reason may be due to the global underestimation of $\sigma_R$ found at intermediate energies in the Glauber model [33]. Different method has been tried to correct this problem [4, 30, 34]. These corrections are performed for almost light stable nuclei. The $\sigma_R$ of $^{24}$Al is calculated with the size of its $^{23}$Mg core determined by fitting $\sigma_I$ at around 1A GeV [31]. But the calculated $\sigma_R$ for $^{24}$Al is only 1430 mb which is $\sim$ 10% lower than the present data. It was shown that scope of the discrepancy between the Glauber model calculation and experimental data is large even for stable nuclei [35]. To correct the possible underestimation for nuclei with $A > 20$, we adjusted the range parameter to fit the $\sigma_R$ of $^{24}$Al from the present measurement. And $\beta = 0.8$ fm is obtained when the $\sigma_R$ of $^{24}$Al at 74A MeV is reproduced. Using this range parameter, the calculated $\sigma_R$ value of $^{23}$Al is still smaller than the data. Similar puzzle is also encountered for some neutron-rich nuclei. The large $\sigma_I$ cannot be reproduced by the FBGM even for the valence neutron in the s-wave for $^{19}$C and $^{23}$O. One way is to enlarge the core size to reproduce the experimental $\sigma_R$ [32, 33]. Here we changed the core size by adjusting width parameters in the HO density distribution of $^{22}$Mg. The dependence of $\sigma_R$ for $^{23}$Al on the core size is calculated and shown in Fig. 6. The calculated results indicate that the core size is $3.13 \pm 0.18$ fm when the experimental $\sigma_R$ data of $^{23}$Al is reproduced ($8\pm 7\%$ larger than the size of the bare $^{22}$Mg nucleus).

In order to reproduce the $\sigma_R$ of $^{23}$Al from the current work, a larger sized core is deduced within the framework of the spherical Glauber model. It should be pointed out that this enlarged core may not necessarily reflect increased physical size of the nucleus. The negligence of some specific effects in the Glauber model could lead to the larger sized core. The possible reasons for the enlargement will be discussed qualitatively below. The effect of quadrupole deformation ($\beta_2$, the parameter describing the deformation) on the rms radius can be expressed as $R_{\text{rms}}^{\beta_2} = \sqrt{(1 + \frac{5}{4\pi}\beta_2^2)R_{\text{rms}}^{0\%}}$ [37]. As shown in the inset of Fig. 6 $R_{\text{rms}}$ of the core changes quickly with the increase of $\beta_2$. This simple relationship between $R_{\text{rms}}$ and $\beta_2$ indicates that a deformed core inside $^{23}$Al will give a larger sized $^{22}$Mg. In order to reproduce the $\sigma_R$ of $^{23}$Al, the lower limit of $R_{\text{rms}}$ for the core is 2.95

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**FIG. 5:** (Color online) The dependence of FWHM for the $P_{1/2}$ distribution after one-proton removal of $^{23}$Al on the separation energy of the valence proton. The solid circles with error bars is result of the present experiment, the shaded area refers to error of the data. The solid and open squares are the FBGM calculations for the $d$ and $s$-wave configuration of the valence proton with the core $R_{\text{rms}} = 3.6$ fm. The solid and open triangles are for the core $R_{\text{rms}} = 2.89$ fm. The lines are just for guiding the eyes. The two arrows refer to the separation energy of 0.125 MeV and 1.37 MeV (the excitation energy for the first excited state of $^{22}$Mg plus the experimental one proton separation energy of $^{23}$Al).

**FIG. 6:** (Color online) The dependence of $\sigma_R$ at 74A MeV on the core size ($R_{\text{rms}}$). The horizontal line is the experimental $\sigma_R$ value, the shadowed area is the error of $\sigma_R$. The triangles denote the FBGM calculations. The size of $^{22}$Mg obtained by fitting the $\sigma_I$ data at around 1A GeV is marked by an arrow. The inset shows the relationship between the quadrupole deformation parameter ($\beta_2$) and size of the core, for details see the text.
fn as we can see from the calculated results in the figure. If we assume that the shape of $^{22}\text{Mg}$ as a nucleus is spherical and enlargement of the core is due to deformation, the lower limit of $\beta_2 = 0.3$ for the core could be deduced from the inset of Fig. 1. Deformation of $\beta_2 = 0.6$ will give around 8% larger radius for the $^{22}\text{Mg}$ core. The experimental and theoretical investigations have demonstrated the deformation for $^{22}\text{Mg}$. The experimental $\beta_2$ is 0.566 [38], the calculated $\beta_2$ by RMF and generalized hybrid derivative coupling model are around 0.4 and 0.6, respectively [39, 40]. If the bare nucleus $^{22}\text{Mg}$ is deformed, the above analysis indicates that $^{22}\text{Mg}$ as a core in $^{23}\text{Al}$ may have larger deformation as compared with $^{22}\text{Mg}$ as a nucleus. Additionally, the first excited state of $^{22}\text{Mg}$ was calculated within the RMF framework and its $R_{\text{rms}}$ is obtained to be around 2.4% larger than that of the ground state [41, 42]. Thus the core excitation effect may also contribute to the larger size for $^{22}\text{Mg}$. As demonstrated by the shell model calculations, the configuration of $^{22}\text{Mg}$ (ground state) plus a $d$-wave proton is dominant in $^{23}\text{Al}$ [24]. If deformation and excitation effects exist in the core, the first one may be the main component.

In summary, the longitudinal momentum distribution of fragments after one-proton removal for $^{23}\text{Al}$ and reaction cross sections for $^{23,24}\text{Al}$ were measured. An enhancement was observed for the $\sigma_R$ of $^{23}\text{Al}$. The $P_{1/2}$ distributions were found to be wide and consistent with the Goldhaber model’s prediction. The experimental $P_{1/2}$ and $\sigma_R$ results were discussed within framework of the Few-Body Glauber model. We determined the valence proton to be a dominant $d$-wave configuration in the ground state of $^{23}\text{Al}$. It indicates no halo structure in this nucleus. But a larger sized $^{22}\text{Mg}$ core was deduced in order to explain both the $\sigma_R$ and $P_{1/2}$ distributions within framework of the spherical Few-Body Glauber model. It is pointed out that deformation and core excitation effects may be two main reasons for the extracted larger sized core. Further theoretical investigations are needed to extract more specific structure information for $^{23}\text{Al}$ from the experimental data.

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