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Different mechanism of two-proton emission from proton-rich nuclei ^{23}Al and ^{22}Mg

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ABSTRACT

Two-proton relative momentum (q_{pp}) and opening angle (θ_{pp}) distributions from the three-body decay of two excited proton-rich nuclei, namely $^{23}\text{Al} \to \text{p} + \text{p} + {}^{21}\text{Na}$ and $^{22}\text{Mg} \to \text{p} + \text{p} + {}^{20}\text{Ne}$, have been measured with the projectile fragment separator (RIPS) at the RIKEN RI Beam Factory. An evident peak at $q_{pp} \sim 20$ MeV/c as well as a peak in θ_{pp} around 30° are seen in the two-proton break-up channel from a highly-excited ^{22}Mg. In contrast, such peaks are absent for the ^{23}Al case. It is concluded that the two-proton emission mechanism of excited ^{22}Mg is quite different from the ^{23}Al case, with the former having a favorable diproton emission component at a highly excited state and the latter dominated by the sequential decay process.

1. Introduction

The decay of proton-rich nuclei, especially the two-proton ($2p$) radioactivity [1], is an interesting process that may be observed in nuclei beyond or close to the proton dripline [2–4]. Generally, there are two main ways for proton-rich nuclei to emit two protons: (i) two-body sequential emission; (ii) three-body simultaneously emission. But in the second way, there is an extreme case with the emission of two strongly correlated protons (called 'diproton'). The diproton emission is basically two protons constrained by the pair correlation in a quasi-bound s-singlet, i.e., $^1S_0$ configuration. Because of the Coulomb barrier, such a quasi-bound state can only exist for a short while and then becomes separated after penetrating through the barrier. Studying the two-proton correlation also provides a good tool to understand the nucleon–nucleon pair-correlation (p–p correlation in particular) inside a nucleus and other related topics like the BCS-BEC crossover [5]. In addition, it is a good way for investigating the astro-nuclear $(2\text{p}, \gamma)$ and $(\gamma, 2\text{p})$ processes which are closely related to the waiting point nuclei [6–8]. Although some experimental investigations on the $2p$ emitter have been done [9–17], the two-proton decay mechanism is still not well understood and further experimental and theoretical studies are required.

Kinematically complete decay channels of cold or low-excited nuclei can be reconstructed by advanced detector arrays. For instance, the three-body decay channel of $\text{p} + \text{p} + {}^{A-2}_{Z-2}\text{Y}$ from a proton-rich nucleus ^A_ZX can be identified by the Si-strip and other ΔE multi-detectors combination, which then allows for the

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measurement of the opening angle, relative momentum and correlation function between two protons. Since protons are not emitted chaotically in the two-proton decay, p–p coincidence measurements can, in principle, deliver information of decay mode or nuclear structure, especially for proton–proton correlation of the parent nucleus [18]. As mentioned above, diproton emission is of interest. In this case, a strong correlation of p–p relative momentum around 20 MeV/c will emerge together with a small opening angle between the two protons in the rest frame of the three decay products as demonstrated in the experimental studies of ^{17,18}Ne [12–14].

Generally, the diproton emission process from the ground state is rare. If the lifetime is long enough, this is also called two-proton radioactivity which was observed in a few nuclei [2,3]. Two-proton radioactivity is predicted to occur for the even-Z nuclei, for which, due to the pairing force, one proton emission is energetically forbidden, whereas two-proton emission is allowed. As this type of two-proton emission is essentially governed by the Coulomb and centrifugal barriers, a sizable lifetime, which is compatible with the concept of radioactivity, is expected only for nuclei with a reasonably high Coulomb barrier. On the other hand, diproton emission itself is a more general phenomenon, especially for excited states in proton-rich nuclei since the decay is less suffered by the Coulomb barrier.

The proton-rich nucleus ^{23}Al has also attracted a lot of attention in recent years since it may play a crucial role in understanding the depletion of the NeNa cycle in ONe novae [19–21]. The measurement of its reaction cross section and fragment momentum distribution has shown that the valence proton in ^{23}Al is dominated by the d wave but with an enlarged core [22,23]. The spin and parity of the ^{23}Al ground state was found to be $J_\pi = 5/2^+$ [19,24]. Also of great interest is ^{22}Mg because of its importance in determining the astrophysical reaction rates for ^{21}Na(p, γ)^{22}Mg and ^{18}Ne(α, p)^{21}Na reactions in the explosive stellar scenarios [25, 26].

In this Letter, we present an exclusive measurement to select the three-body decay channels of ^{23}Al and ^{22}Mg, and investigate the relative momentum and opening angle between the two protons. Based on the previous studies, a specific excitation energy window of $10.5 < E^* < 15$ MeV is used for ^{23}Al and while $12.5 < E^* < 18$ MeV for ^{22}Mg, respectively. The window selections are based on (1) the data table of ^{23}Al shows the existence of an excited state of 11.780 MeV where two-proton emission may exist [27]; (2) the transitions from the ^{22}Mg ($T = 2$) analog state (the excitation energy is 14.044 MeV) to the ground state and/or first excited state of ^{20}Ne was claimed but they were unable to distinguish diproton emission or sequential protons emission [28]. Our results show a different two-proton emission mechanism of ^{23}Al and ^{22}Mg as well as a clear diproton component from the decay of ^{22}Mg at high excitation energy, which demonstrates an interesting phenomenon.

2. Experiments

The experiment was performed using the RIPS beamline at the RI Beam Factory (RIBF) operated by RIKEN Nishina Center and Center for Nuclear Study, University of Tokyo. The secondary ^{23}Al and ^{22}Mg beams with incident energy of 57.4A MeV and 53.5A MeV, respectively, were generated by projectile fragmentation of 135A MeV ^{28}Si primary beam on ^{9}Be production target and then transported to a ^{12}C reaction target. Around the reaction target, there was a γ detector array of 160 NaI(Tl) scintillator crystals named DALI2. After DALI2 there were five layers of silicon detectors. The first two layers of Si-strip (5 mm width for one strip, 10 strips for one detector) detectors located around 50 cm downstream of the target were used to measure the emitting angle of the fragment and protons. Three layers of 9 single-electrode Si were used as the ΔE–E detectors for the fragment. Each Si-strip layer consists of 5×5 matrix without detectors in the four corners. While each element Si layer consists of 3×3 matrix. Three layers of plastic hodoscopes located around 3 m downstream of the target were used as ΔE and E detectors for protons. Time-of-flight (TOF) of proton was measured by the first layer. Most of the protons were stopped in the second layer.

The particle identification of ^{23}Al and ^{22}Mg before the reaction target was done by means of $B\rho$–ΔE-TOF method. After the reaction target, the heavy fragments were identified by five layers of silicon detectors through the ΔE–E technique. Fragments with different charge and mass number are well separated. Both the emission angle and energy loss can be obtained for the fragments. Total energy of heavy fragments can be obtained by summing over the energy loss of the five layers of silicon detector. Details about the experimental information can be found in Ref. [29]. From this setup, a resolution better than 5 MeV/c of the relative momentum for protons at the typical energy of 65 MeV can be achieved.

Clear particle identification were obtained for both the heavy fragments and protons. The exclusive measurement for the breakup of the incident radioactive beam can be realized. In our analysis, the $(\mathrm{p}+\mathrm{p}+{}^{A-2}_{Z-2}\mathrm{Y})$ reaction channel can be picked and the excitation energy of the incident nucleus ${}^{A}_{Z}\mathrm{X}$ can be reconstructed by the difference between the invariant mass of three-body decay channel and mass of the mother nucleus in the ground state. Fig. 1(a) and Fig. 1(b) show the excitation energy distribution obtained for the two proton emission channel of ^{23}Al and ^{22}Mg, respectively. Since the resolution for the reconstructed excitation energy is estimated to be ∼1 MeV, it is difficult to identify the specific excited states in ^{23}Al and ^{22}Mg.

3. Results and discussion

In the present study, we firstly examine the relative momentum spectrum (q_{pp}) and opening angle (θ_{pp}) of the two protons in the rest frame of three-body decay system for odd-Z nucleus ^{23}Al and even-Z nucleus ^{22}Mg without any cut in the excitation energy. A broad q_{pp} spectrum and structure-less θ_{pp} distribution are observed as shown in the insets of Fig. 1(a) and Fig. 1(b). These results indicate that the dominant mechanism of two proton emission from ^{23}Al and ^{22}Mg are sequential or simultaneous decay with weak correlation between the two protons. Since the decay mode for different excited state or excitation energies could be different, it will be interesting to check q_{pp} and θ_{pp} spectra in some excitation energy windows. For diproton emission, a clear peak should appear at relative momentum around ∼20 MeV/c as well as small opening angle. Fig. 2 shows the result of the above two distributions for ^{23}Al in excitation energy window $10.5 < E^* < 15$ MeV. Evident peaks at $q_{pp} \sim 20$ MeV/c (Fig. 2(a)) and smaller opening angle (Fig. 2(b)) are absent. Instead, the q_{pp} spectrum is broad and the θ_{pp} distribution is structure-less which are very similar to the results of the whole excitation energy distribution. Similar analysis has been checked in different E* windows other than $10.5 < E^* < 15$ MeV and similar behaviors for q_{pp} and θ_{pp} are observed.

Results have also been obtained for the even-Z proton-rich nucleus, ^{22}Mg. Fig. 3 shows the relative momentum spectrum and opening angular distribution for the channel of $\mathrm{p}+\mathrm{p}+{}^{20}\mathrm{Ne}$ in the excitation energy window $12.5 < E^* < 18$ MeV. The peaks of the relative momentum distribution at 20 MeV/c (Fig. 3(a)) and of the corresponding smaller opening angle (Fig. 3(b)) are clearly observed. These features are consistent with the diproton emission mechanism. However, no significant enhancements for

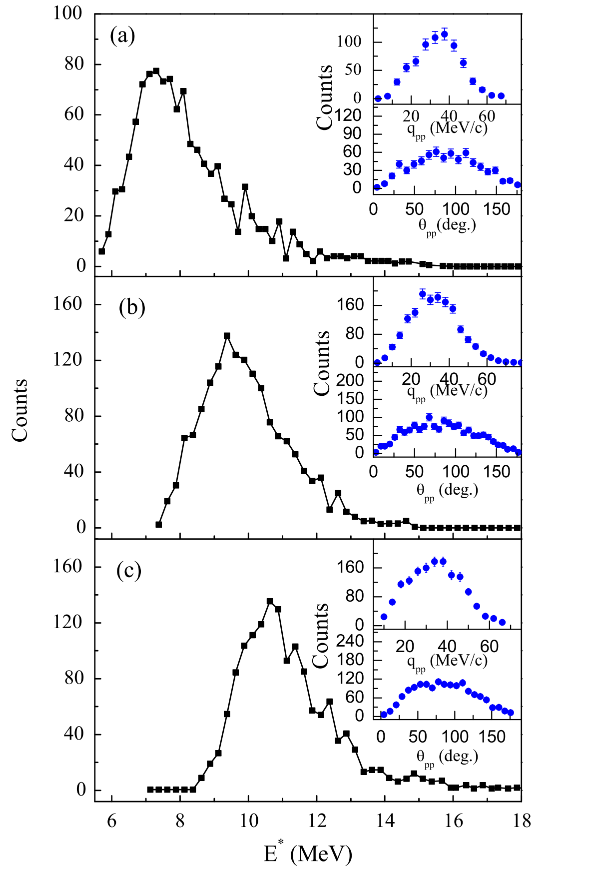

Fig. 1. (Color online.) The excitation energy distributions constructed by the invariant mass of two-proton emission process for ^{23}Al (a), ^{22}Mg (b) and $^{23}\mathrm{Al} \to \mathrm{p} + \mathrm{p} + {}^{20}\mathrm{Ne}$ (c). The relative momentum and opening angle distributions of two protons are given in the inset of (a), (b) and (c), respectively.

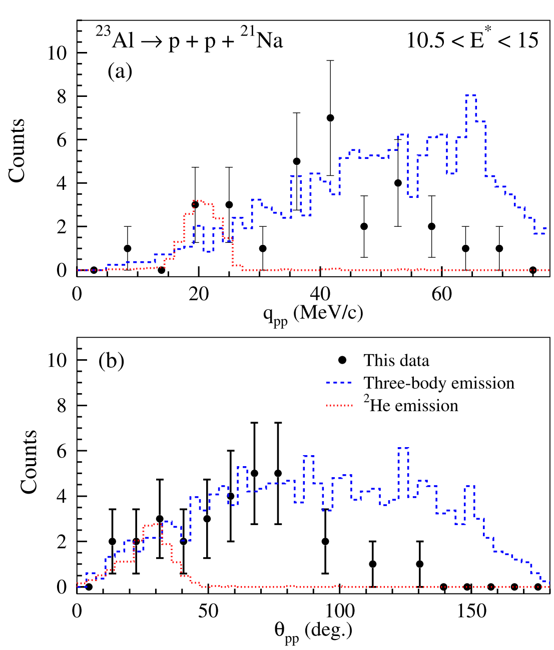

Fig. 2. (Color online.) Relative momentum distribution of two protons produced by the decay of ^{23}Al into two protons plus ^{21}Na in the excitation energy window $10.5 < E^* < 15$ MeV (a); Opening angle distribution between the two protons in the same excitation energy window (b).

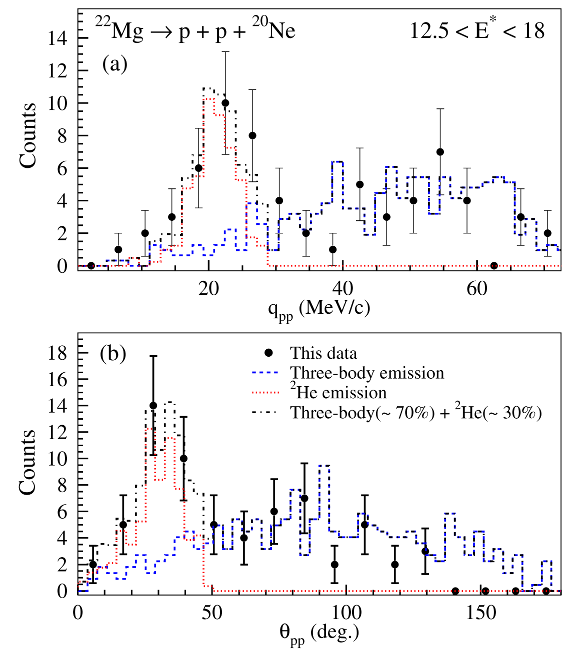

Fig. 3. (Color online.) Same as Fig. 1 but for ^{22}Mg in the excitation energy window $12.5 < E^* < 18$ MeV.

$q_{pp} \sim 20$ MeV/c and small θ_{pp} are observed for other E^* windows, which illustrates that the importance of the specific window $12.5 < E^* < 18$ MeV for diproton emission of ^{22}Mg.

In order to quantitatively understand the q_{pp} and θ_{pp} spectra, Monte Carlo simulations have been performed. As shown in Fig. 1, the excitation energy spectrum is almost continuous, it is difficult to distinguish the sequential decay from the weak correlation simultaneous emission in our measurements. Only two extreme cases are considered, i.e., diproton and weak correlation simultaneous three-body decay. In the Monte Carlo simulation for ^{22}Mg, the diproton decay spectrum was obtained by randomly sampling the phase-space of the two-step process, $^{22}\mathrm{Mg} \to {}^{2}\mathrm{He} + {}^{20}\mathrm{Ne} \to \mathrm{p} + \mathrm{p} + {}^{20}\mathrm{Ne}$, with the constraints of energy and momentum conservation and diproton being in the singlet-S resonant of two protons (^{2}He). The relative energy of the diproton was simulated according to Ref. [30]. The simultaneous three-body decay was simulated in the same way except that the phase-space of the three-body $\mathrm{p} + \mathrm{p} + {}^{20}\mathrm{Ne}$ is sampled with only the constraints of energy and momentum conservation. In Fig. 2 and Fig. 3, we show the diproton component by the dotted line and the three-body component by the dashed line. As shown in Fig. 2, no trace for diproton emission is visible for ^{23}Al as discussed before. For ^{22}Mg, on the other hand, the diproton emission peaks are well reproduced by the simulation. The dash-dotted histograms in Fig. 3 represent the mixing of the two components. The fraction of the diproton emission is about 30%. In similar previous experiments, around 70% diproton emission contribution from highly excited ^{17}Ne was deduced [12] and around 30% diproton emission contribution from the 6.15 MeV (1^-) state of ^{18}Ne was observed [14].

Even though our excitation energy data is not precise enough to identify the exact excited state, the selected excitation energy window $10.5 < E^* < 15$ MeV covers the 11.780 MeV excited state of ^{23}Al [27]. Our observation illustrates that diproton emission is not visible in ^{23}Al. Since ^{23}Al is an odd-Z proton-rich nucleus, the diproton emission is relatively difficult in comparison with the even-Z proton-rich nucleus ^{22}Mg. In a previous β-delayed proton emission experiment for ^{22}Al, two-proton emission has been established but the decay mechanism is uncertain [28]. Our data

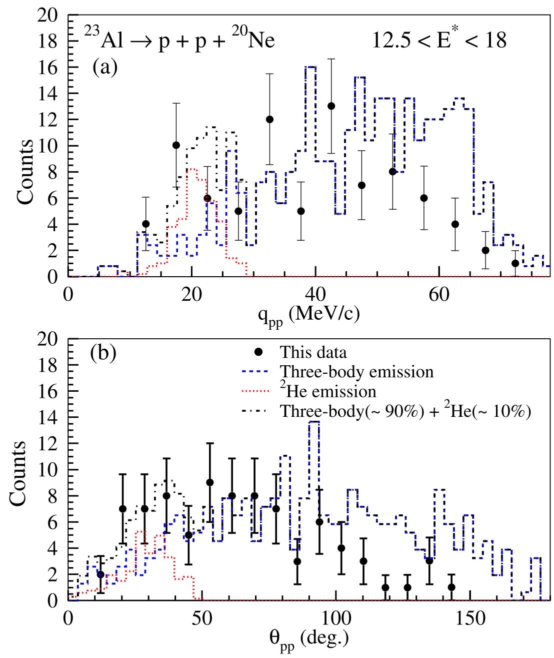

Fig. 4. (Color online.) Same as Fig. 2 but for $^{23}Al \to p + p + {}^{20}Ne$ in the excitation energy window $12.5 < E^* < 18$ MeV.

confirm that there indeed exists diproton emission (two-protons coupled to a $^1S_0$ configuration) by the observation of the peak at $q_{pp} \sim 20$ MeV/c together with the small opening angles between the two protons only in the excitation energy window $12.5 < E^* < 18$ MeV, which covers the 14.04 MeV state of ^{22}Mg with two-proton emissions. On the whole, our present experiment definitely demonstrates that there exists a remarkable component of diproton emission process in the proton-rich nucleus ^{22}Mg.

Considering excited ^{22}Mg can also be produced by the single-proton removal from ^{23}Al, it provides us an alternative way to check the proton emission mechanism by the decay process of $^{23}Al \to p + p + {}^{20}Ne$, where one proton was not detected in our experimental setup. In Fig. 1(c), the excitation energy spectrum for this process was shown together with the q_{pp} and θ_{pp} distributions. From the q_{pp} and θ_{pp} spectra, a very small increase of statistics at $q = 20$ MeV/c and small opening angle can be seen. To see more clearly, the relative momentum and opening angle distributions between two protons in the excitation energy window $12.5 < E^* < 18$ MeV were shown in Fig. 4. A moderate enhancement appears at $q_{pp} \sim 20$ MeV/c in Fig. 4(a) and small angle in Fig. 4(b), which can be understood assuming the following two-step proton decay mechanism from ^{23}Al. First, one proton was emitted from ^{23}Al and its corresponding residue nucleus is ^{22}Mg. Then other two protons are ejected from ^{22}Mg and its corresponding residue nucleus is ^{20}Ne. Because of a remarkable $2p$ correlation emission component in the second decay channel (Fig. 3), a moderate $2p$ enhancement could be eventually observed in the process of $^{23}Al \to p + p + {}^{20}Ne$. The peak height of q_{pp} in Fig. 4(a) can be seen as a mixture of Fig. 2(a) and Fig. 3(a), corresponding to events which have one proton from the first decay step and another proton from the second decay step. Actually a 10% fraction of diproton emission can reproduce the data quite well as shown by the dash-dotted histograms in Fig. 4.

4. Conclusions

The measurements on two-proton relative momentum and opening angle from the decay of the excited ^{23}Al and ^{22}Mg have been performed at the RIKEN RIBF. In order to explore the internal proton–proton correlation information inside excited proton-rich nuclei, decay channels of $^{23}Al \to p + p + {}^{21}Na$ and $^{22}Mg \to p + p + {}^{20}Ne$ have been selected. The results on the relative momentum and opening angle between the two protons are presented. A broad q_{pp} spectrum and structure-less θ_{pp} distribution are observed for the whole excitation energy distribution which is reconstructed by the invariant mass method. Peaks around $q_{pp} \sim 20$ MeV/c and $\theta_{pp} \sim 30°$ are clearly observed for the even-Z ^{22}Mg at $12.5 < E^* < 18$ MeV covering the 14.044 MeV excited state with $T = 2$, which can be explained by a component of diproton emission. For the odd-Z proton-rich nucleus ^{23}Al, the sequential decay is overwhelmingly dominant. These results are confirmed by looking at the intermediate state of ^{22}Mg in the process of $^{23}Al \to p + p + {}^{20}Ne$.

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