Proton-proton correlations in distinguishing the two-proton emission mechanism of $^{23}$Al and $^{22}$Mg

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The proton-proton momentum correlation functions ($C_{pp}(q)$) for kinematically complete decay channels of $^{23}$Al $\rightarrow$ p + p + $^{21}$Na and $^{22}$Mg $\rightarrow$ p + p + $^{20}$Ne have been measured at the RIKEN RI Beam Factory. From the very different correlation strength of $C_{pp}(q)$ for $^{23}$Al and $^{22}$Mg, the source size and emission time information were extracted from the $C_{pp}(q)$ data by assuming a Gaussian source profile in the correlation function calculation code (CRAB). The results indicated that the mechanism of two-proton emission from $^{23}$Al was mainly sequential emission, while that of $^{22}$Mg was mainly three-body simultaneous emission. By combining our earlier results of the two-proton relative momentum and the opening angle, it is pointed out that the mechanism of two-proton emission could be distinguished clearly.

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I. INTRODUCTION

The two-particle intensity interferometry has been extensively utilized to determine the space–time extension of particle emitting sources in nuclear and particle physics over the past several decades [1–10]. In heavy ion collisions, the two-particle interferometry is a well-recognized and powerful method to characterize the source of particle emission and to probe and disentangle different reaction mechanisms. In particular, this method can provide information on the space–time evolution of hot nuclei which usually decay by evaporation and/or (multi-)fragmentation. Even though a large number of experiments have been carried out to measure the two-proton correlation in nuclear fragmentation, almost no proton-proton momentum correlation function measurement was reported for a kinematically complete decay channel. In contrast, there have been several measurements of the neutron-neutron momentum correlation function in kinematically complete decay channels for halo nuclei, such as $^{11}$Li [11,12] and $^{14}$Be [12], which were believed to be useful for studying the so-called di-neutron structure of neutron-rich nuclei [14].

The phenomenon of two-proton emission is a very interesting but complicated process existing in the nucleus close to the proton-drip line [13–19]. The proton-proton correlation plays an important role in the emission mechanism. There is a distinct difference in the spectra of the two-proton relative momentum ($q_{pp}$) and opening angle ($\theta_{pp}$) between the diproton emission and two-body sequential or three-body simultaneous emission. This characteristic has been used to investigate the mechanism of two-proton emissions [20,21].

The proton-rich nuclei $^{23}$Al and $^{22}$Mg are very important in determining some astrophysical reaction rates and have attracted a lot of attention in both astrophysics and nuclear structure studies [22–29]. Recently, we have reported the experimental results for kinematically complete measurements of two-proton emissions from two excited proton-rich nuclei, namely $^{23}$Al $\rightarrow$ p + p + $^{21}$Na and $^{22}$Mg $\rightarrow$ p + p + $^{20}$Ne [30]. Based on the analysis of $q_{pp}$ and $\theta_{pp}$ distributions of the two emitted protons, a favorable diproton emission component from the excited states around 14.044 MeV of $^{22}$Mg was observed. But no such signal exhibited in the two-proton emission processes of the excited $^{23}$Al.

As pointed out in Ref. [30], it is difficult to distinguish between the two-body sequential and three-body simultaneous emission mechanism using the above analysis. In these two mechanisms, the emission time of the two protons is quite different. For three-body simultaneous
emission, the two protons are emitted almost at the same
time, while the two protons are emitted one by one in se-
quential emission. The two-particle intensity interferom-
etry method has been demonstrated to be a good way to
extract the source size and particle emission time [31, 32].
In this paper, the proton-proton momentum correlation
function will be studied for the three-body decay chan-
nels $^{23}\text{Al} \rightarrow p + p + ^{21}\text{Na}$ and $^{22}\text{Mg} \rightarrow p + p + ^{20}\text{Ne}$. The size and emission time information of the source will
be extracted. The possibility of distinguishing sequential and three-body simultaneous emission mechanism will be
investigated.

II. EXPERIMENT DESCRIPTION

The experiment was performed using the RIPS beam-
line at the RI Beam Factory (RIBF) operated by RIKEN
Nishina Center and Center for Nuclear Study, University
of Tokyo. A primary beam of 135 A MeV $^{28}\text{Si}$ was used
to produce secondary $^{23}\text{Al}$ and $^{22}\text{Mg}$ beams with incident energy of 57.4 A MeV and 53.5 A MeV in the center
of the carbon reaction target, respectively. After the re-
action target, there were five layers of silicon detectors and three layers of plastic hodoscopes as shown in Fig. 1.
The first two layers of Si-strip detectors located around
50 cm downstream of the target were used to measure the emitting angle of the fragment and protons. Three
layers of $3 \times 3$ single-electrode Si were used as the $\Delta E$-$E$
detectors for the fragment. The three layers of plastic
hodoscopes located around 3 m downstream of the tar-
get were used as $\Delta E$ and $E$ detectors for protons. TOF
of proton was measured by the first layer. Clear particle
identifications were obtained by this setup for the kinematically complete three-body decay reactions. The mo-
mentum and emission angle for protons and the residue
are determined by analyzing the detector signals. The
excitation energy ($E^*$) of the incident nucleus was re-
constructed by the difference between the invariant mass
of three-body system and mass of the mother nucleus in
the ground state. More detailed description of the exper-
iment could be found in Ref. [30].

![FIG. 1: (Color online) The layout of detector setup. For
details see the text.](image)

III. RESULTS AND DISCUSSION

In the present study, the momentum correlation func-
tions between two protons emitted from $^{23}\text{Al}$ and $^{22}\text{Mg}$
are studied. Experimentally, the two-proton correlation
function is constructed through dividing the coinci-
dence yield $N_c$ by the yield of non-correlated events $N_{nc}$,

$$C_{pp}(q) = K \frac{N_c(q)}{N_{nc}(q)},$$

where the relative momentum is given by $q = \frac{1}{2}||p_1 - p_2||$, with $p_1$ and $p_2$ being the mo-
menta of the two coincident protons. The normaliza-
tion constant $K$ is determined so that the correlation function goes to unity at large values of $q$, where no correlation is
expected.

The event-mixing technique was applied to con-
struct the background yield, i.e. by pairing a proton with
a randomly chosen uncorrelated proton from different
events and then normalized to the number of two-proton
correlation events in $N_c$. This method ensures that the
uncorrelated distribution includes the same class of col-
lisions and kinematical constraints as the numerator. It
has, however, a potential problem: it may attenuate the
slight correlations one wishes to measure due to the ex-
istence of possible "residue correlation" from initial two-
proton physical correlation, which will overestimate the
denominator. To eliminate this "residue correlation", an
iterative calculation method for the $C_{pp}(q)$ was applied
and intrinsic correlation was extracted. A similar
method has been first applied to two-neutron momen-
tum correlation function measurement for neutron-halo nuclei [33]. Here it is the first attempt to apply the cor-
relation function analysis on two-proton emission data.

Firstly, we looked at the two-proton correlation in the
inclusive reaction channel which is similar to the proton-
proton momentum correlation function for hot nuclei.

![FIG. 2: (Color online) The proton-proton momentum corre-
lation function ($C_{pp}(q)$) for the reaction channel of $^{23}\text{Al} \rightarrow p + p + X$ (a) and $^{22}\text{Mg} \rightarrow p + p + X$ (b). The dots are ex-
pperimental data. The lines are the calculations by the CRAB
code with a Gaussian source.](image)
Fig. 2 showed our measurements of $C_{pp}(q)$ which were obtained by the event-mixing method with an iterative calculation for the two emitted protons, without identifying the residue from the mother nucleus and using any specific $E^*$ window. Fig. 2(a) and Fig. 2(b) were the results for the inclusive channel of $^{23}\text{Al} \rightarrow p + p + X$ and $^{22}\text{Mg} \rightarrow p + p + X$, respectively. In this work, the normalization factor $K$ in calculating $C_{pp}(q)$ was determined by the $50 < q_{pp} < 100$ MeV/c data. The peak height around $q_{pp} = 20$ MeV/c reflected the strength of correlation function. To extract the source size, theoretical calculation for $C_{pp}(q)$ was performed by using the correlation function calculation code (CRAB) \[34\]. A Gaussian profile was assumed for the source and the space distribution was simulated according to the function $S(r) \sim \exp(-r^2/2r_0^2)$, with $r_0$ being the source size parameter. The calculations were compared with the experimental $C_{pp}(q)$ data. The source size was determined by finding the minimum of the reduced chi-square ($\chi^2/\nu$, $\nu$ is the degree of freedom). The fit gave a source size range of $r_0 = 3.15 \sim 3.25$ fm for $^{23}\text{Al}$ (corresponding to the rms radius of $R_{rms} = 5.46 \sim 5.63$ fm). The uncertainty was determined from the minimum chi-square $\chi_0^2$ to $\chi^2 + 1$. The best fit of the calculation was plotted in the figure. The obtained source size could give us information of the average distance between the two emitted protons. This size is much larger than the expected radius of the $^{23}\text{Al}$ nucleus. Of course, a caution needs to be taken for the value of $r_0$, which should be considered as the apparent size for the source since the emission time between two protons is another folded ingredient. For $^{22}\text{Mg}$, the source size was extracted to be $r_0 = 2.9 \sim 3.0$ fm which is a little bit smaller than that of $^{23}\text{Al}$.

Secondly, we checked the kinematically complete three-body channels for both $^{23}\text{Al}$ and $^{22}\text{Mg}$. Fig. 3 showed the $C_{pp}(q)$ of the two emitted protons which were coincident with the residues from the mother nuclei. For the channel of $^{23}\text{Al} \rightarrow p + p + ^{21}\text{Na}$, Fig. 3(a) showed an almost flat correlation function except for the Coulomb dip in low $q_{pp}$ region, indicating that emission of both protons from $^{23}\text{Al}$ three-body break-up was uncorrelated in phase space except for the Coulomb interaction. This was consistent with the result of no clear observation of diproton emission from the relative momentum and opening angle spectra of $^{23}\text{Al}$ at any excited states \[30\]. Generally speaking, a flat proton-proton momentum correlation function indicates a very large source size and very weak two-proton correlation. The $C_{pp}(q)$ data was also compared with the Gaussian source calculations. The fit gave a source size $r_0 = 3.9 \sim 4.7$ fm which was larger than that of the inclusive channel of $^{23}\text{Al}$, indicating a more loose two-proton emission. Since the effect of emission time was not considered, it is difficult to explain the results only by the geometric size of the source.

In contrast, the $C_{pp}$ data for $^{22}\text{Mg}$ nucleus was very different from that of $^{23}\text{Al}$ as shown in Fig. 3(c). In this figure, a strong correlation emerged in $C_{pp}$ spectra for the process of $^{22}\text{Mg} \rightarrow p + p + ^{20}\text{Ne}$, which indicated a compact source size of two-proton emission. The fit gave $r_0 = 2.35 \sim 2.45$ fm, which was smaller than that of the inclusive channel of $^{22}\text{Mg}$.

Between the two very different two-proton correlation pattern of $^{23}\text{Al}$ and $^{22}\text{Mg}$, we had checked the intermediate situation. If we looked at the decay process of $^{23}\text{Al} \rightarrow p + p + ^{20}\text{Ne}$, where one proton was not detected by the experimental setup, a moderate correlation appeared at $q_{pp} \sim 20$ MeV/c as shown in Fig. 3(b), which could be understood by assuming the following two-step proton emission process of $^{23}\text{Al}$. One proton was emitted from $^{23}\text{Al}$ and its corresponding residue nucleus was $^{22}\text{Mg}$; Then the other two protons were ejected from $^{22}\text{Mg}$ and its corresponding residue nucleus was $^{20}\text{Ne}$. Among the three emitted protons, only two protons were detected by the detectors. Because of a strong two-proton correlation in the second step, a moderate two-proton correlation could be eventually observed in the process of $^{23}\text{Al} \rightarrow p + p + ^{20}\text{Ne}$. The peak height of $C_{pp}$ in Fig. 3(b) could be explained by a mixture of Fig. 3(a) and Fig. 3(c). The Gaussian source fit gave a size of $r_0 = 3.1 \sim 3.3$ fm, which was between the cases of Fig. 3(a) and Fig. 3(c). In addition, to give a visual impression of two-proton emission, the sketch maps were plotted as inserts in Fig. 3 to illustrate the most probable emission mechanism for each channel.

The effective source size was extracted from the above analysis. However, it was not sure how the two pro-
τ refers to the lifetime for the emission of the second proton, which starts from the emission time of the first proton. The agreement between the calculation and the $C_{pp}(q)$ data was evaluated by determining the value of the reduced chi-square. The results were shown in Fig. 4 by a contour plot of $\chi^2/\nu$ as a function of $r_0$ and $\tau$. For the reaction channel of $^{23}\text{Al} \rightarrow p + p + ^{21}\text{Na}$ as shown in Fig. 4(a), the ranges of source parameters were obtained to be $r_0 = 1.2 \sim 2.8$ fm and $\tau = 600 \sim 2450$ fm/c based on the best chi-square fit. While for the reaction channel of $^{22}\text{Mg} \rightarrow p + p + ^{20}\text{Ne}$ as shown in Fig. 4(c), the ranges of source parameters were $r_0 = 2.2 \sim 2.4$ fm and $\tau = 0 \sim 50$ fm/c. It means that the emission time difference between two protons for $^{23}\text{Al}$ and $^{22}\text{Mg}$ was quite different. For $^{23}\text{Al}$, the two protons were emitted at very different time ($\tau > 600$ fm/c), i.e. the mechanism is a sequential emission. For $^{22}\text{Mg}$, the two protons were emitted almost at the same time ($\tau < 50$ fm/c), i.e. the mechanism was essentially simultaneous. Based on the above results and the $q_{pp}$ and $\theta_{pp}$ analysis in Ref. [30], all observables indicate the three-body simultaneous decay mechanism for $^{22}\text{Mg}$. Moreover, for the excitations around the 14.044 MeV, $T = 2$ state a strong diproton-like component was observed. For the reaction channel of $^{23}\text{Al} \rightarrow p + p + ^{20}\text{Ne}$ as shown in Fig. 4(c), the determined source parameters were $r_0 = 0.4 \sim 2.0$ fm and $\tau = 350 \sim 1950$ fm/c, which were also between the above two cases and could be explained by the two-step proton emission process of $^{23}\text{Al}$.

**IV. CONCLUSIONS**

In summary, measurement on the proton-proton momentum correlation function was applied to kinematically complete decay of two reaction channels $^{23}\text{Al} \rightarrow p + p + ^{21}\text{Na}$ and $^{23}\text{Al} \rightarrow p + p + ^{20}\text{Ne}$ in this paper. The experiment was performed at the RIKEN RI Beam Factory. The proton-proton momentum correlation function $C_{pp}$ was obtained by the event-mixing method with an iterative calculation. By assuming a simple Gaussian emission source, the effective source sizes were extracted by comparing the CRAB calculation with the experimental $C_{pp}$ data. Different effective source size was obtained for $^{23}\text{Al}$ and $^{22}\text{Mg}$, which comes from the different mechanism of two-proton emission. In a more general analysis including source size and emission time information, a reasonable source size but completely different emission time for the two protons were extracted. The results indicated that the mechanism of two-proton emission from $^{23}\text{Al}$ was dominated sequential, while that for $^{22}\text{Mg}$ was mainly three-body simultaneous emission with a strong diproton-like component at excited states around 14.044 MeV. Based on the previous results [30] and this work, it is possible to distinguish clearly the mechanism of two-proton emission by investigating on the proton-proton momentum correlation function, the two-proton relative momentum and opening angle distributions. The method presented in this work was applied for the first time to...
two-proton emitters, and was shown to provide new and valuable information on the mechanism of two-proton emission.

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