

Correlation functions and emission time sequence
of light charged particles from projectile-like fragment source
in $E/A = 44$ and 77 MeV $^{40}\text{Ar} + ^{27}\text{Al}$ collisions

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Abstract

Two-particle correlation functions, involving protons, deuterons, tritons, and α -particles, have been measured at very forward angles ($0.7^\circ \leq \theta_{lab} \leq 7^\circ$), in order to study projectile-like fragment (PLF) emission in $E/A = 44$ and 77 MeV $^{40}\text{Ar} + ^{27}\text{Al}$ collisions. Peaks, originating from resonance decays, are larger at $E/A = 44$ than at 77 MeV, reflecting the larger yields of independently emitted light particles at the higher bombarding energy. The time sequence of the light charged particles, emitted from the PLF, has been deduced from particle-velocity-gated correlation functions (discarding the contribution from resonance decays). α -particles are found to have an average emission time shorter than protons but longer than tritons and deuterons.

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1 Introduction

Extensive studies have demonstrated that non-central heavy-ion collisions at intermediate energies proceed through a dissipative binary reaction mechanism, characterized by early dynamical emission from an intermediate velocity source, followed by statistical evaporation from an excited projectile-like fragment and from an excited target-like fragment [1–7]. In particular, this is true for the reverse kinematics reaction $\text{Ar} + \text{Al}$, investigated by several authors [8–18]. In this paper, we aim to study light charged particle (LCP) emission from the PLF, in $E/A = 44$ and 77 MeV $^{40}\text{Ar} + ^{27}\text{Al}$ collisions. To this end, we investigate experimental two-particle correlation functions of protons, deuterons, tritons and α -particles.

From previous investigations, as well as from kinematical reasons, it is well known that non-central collisions are dominated by PLF emission at very forward angles (see, e.g., the study of LCP emission from $E/A = 60$ MeV $^{40}\text{Ar} + ^{27}\text{Al}$ collisions presented in Ref. [17]). In the present study, the experimental conditions of low detection thresholds, large dynamic range, fine granularity, and small angular separation between the centers of adjacent detectors, allows us to perform the correlation function analysis on a very forward angular range, $0.7^\circ \leq \theta_{lab} \leq 7^\circ$.

Information about the emission times of the different particle types can be deduced from a model-independent analysis of the respective measured correlation functions. In particular, we aim to understand the order of emission of the LCPs from the PLF, by means of particle-velocity-gated correlation functions of non-identical particles [19–21]. This adds an important and novel piece of information to the picture of the

reaction mechanism emerging from previous studies [17,18]. Furthermore, the relative importance of independent two-particle emission, as compared to two-particle decay from preformed fragments, is investigated by comparing the strength of the resonance peaks at the two beam energies.

The paper is organized as follows. After a brief description of the experimental setup and event selection criteria (Sec. 2), we present the results from the data analysis for the $E/A = 44$ and 77 MeV $^{40}\text{Ar} + ^{27}\text{Al}$ collisions. These include LCPs kinetic energy spectra (Sec. 3), correlation functions of identical and non-identical particle pairs (Sec. 4), and particle emission time sequence extracted from the velocity-gated two-particle correlation functions (Sec. 5). Finally, a summary and conclusions are given in Sec. 6.

2 Experimental details

The data analyzed in this paper were taken at GANIL in two separate experiments with different beam energies. $E/A = 44$ and 77 MeV ^{40}Ar pulsed beams impinged on $200 \mu\text{g}/\text{cm}^2$ thick ^{27}Al targets. The reaction products were detected by the ARGOS [18] multidetector system, an array of 112 hexagonal BaF_2 crystals (surface area 25 cm^2) modified into phoswich by means of fast plastic scintillator sheets (700 and $1900 \mu\text{m}$ thick for the two beam energies, respectively).

ARGOS was placed inside the Nautilus vacuum chamber, with the following geometry (which is illustrated in Fig. 1 of Ref. [18]). A forward wall of 60 elements was placed between 0.7° and 7° in a honeycomb shape at a distance of 233 cm from the target (solid angle 0.03 sr). The angular separation between the centers of two adjacent detectors was $\approx 1.5^\circ$. A backward wall of 18 phoswich elements was placed between 160° and 175° , at a distance of 50 cm from the target. Finally, a battery of 30 phoswich elements was placed in plane, at angles between 10° and 150° , at a distance from the target variable from 50 to 200 cm. Further details on the experimental setup can be found in Refs. [18,22,23].

Identification of the reaction products was achieved via shape discrimination of the photomultiplier signals and Time-of-Flight technique [18,22]. LCPs ($Z = 1$ and 2) were isotopically separated, while fragments with $Z \geq 3$ were identified in charge. The particle velocity was directly measured by means of Time-of-Flight technique. The experimental thresholds were set to 2 cm/ns for $E/A = 44$ MeV, and to 3 cm/ns for $E/A = 77$ MeV. The BaF_2 crystals, of variable thickness up to 10 cm, stopped protons of energy up to 200 MeV.

Two slightly different trigger conditions were implemented in the two experiments. In the 44 MeV experiment, events were recorded each time the in-plane detectors or the backward wall was fired, a minimum total multiplicity of 2 being registered. In the

77 MeV experiment, instead, a coincidence between any two detectors was sufficient to start the data acquisition.

In this analysis, the event selection aims to choose semiperipheral collisions. This is achieved by requiring that the pairs of LCPs (p , d , t , and α) detected in the forward wall, must be in coincidence with one PLF (any fragment with atomic charge $3 \leq Z_{PLF} \leq 18$ and velocity within 70% of the beam velocity) also detected in the forward wall¹. The analysis of particle velocity spectra and of invariant cross-sections presented in Refs. [18,23], indicates that this type of events is associated with semiperipheral binary collisions, where two sources, with velocities close to the initial velocity of the projectile and of the target nuclei, are formed. In addition, the mid-rapidity region is an abundant source of particles [18].

3 Kinetic energy distributions of light charged particles

The laboratory kinetic energy distributions of protons, deuterons, tritons, and α -particles, measured in the $E/A = 44$ and 77 MeV $^{40}\text{Ar} + ^{27}\text{Al}$ reactions, are shown in Fig. 1, integrated in the angular range $0.7^\circ \leq \theta_{lab} \leq 7^\circ$. The detection energy thresholds correspond to ≈ 2 and 5 MeV/nucleon for $E/A = 44$ and 77 MeV experiment, respectively.

One can notice several qualitative features:

- 1) The spectra are dominated by a dumb-bell structure, displaying a minimum slightly below the beam energy. This behavior is typical of particles emitted isotropically by a PLF, with a velocity component either parallel to PLF movement (higher energy peak) or antiparallel (lower energy peak) [18]. Because of the Coulomb push from the PLF, these particles will have an energy either higher or lower than the beam energy [24].
- 2) In addition to PLF emission, the spectra also contain contributions from an intermediate velocity source and from a target-like source [18].
- 3) The dumb-bell structure in the energy spectra is more pronounced for p and d and it is slightly suppressed for t and α . This may be expected, since the Coulomb push per particle experienced by an α -particle is less than half that experienced by a proton (taking into account the mass and charge of the α -particle, and its larger average emission distance due to its larger size). In addition, the kinematical focusing at forward angles increases with the mass of the emitted particles, and it is strongest for α -particles [17]. Another effect for the smearing the dumb-bell structure may

¹For the $E/A = 44$ MeV experiment, an additional particle detected in the plane or in the backward detectors is required, since this condition was implemented in the hardware trigger of that experiment.

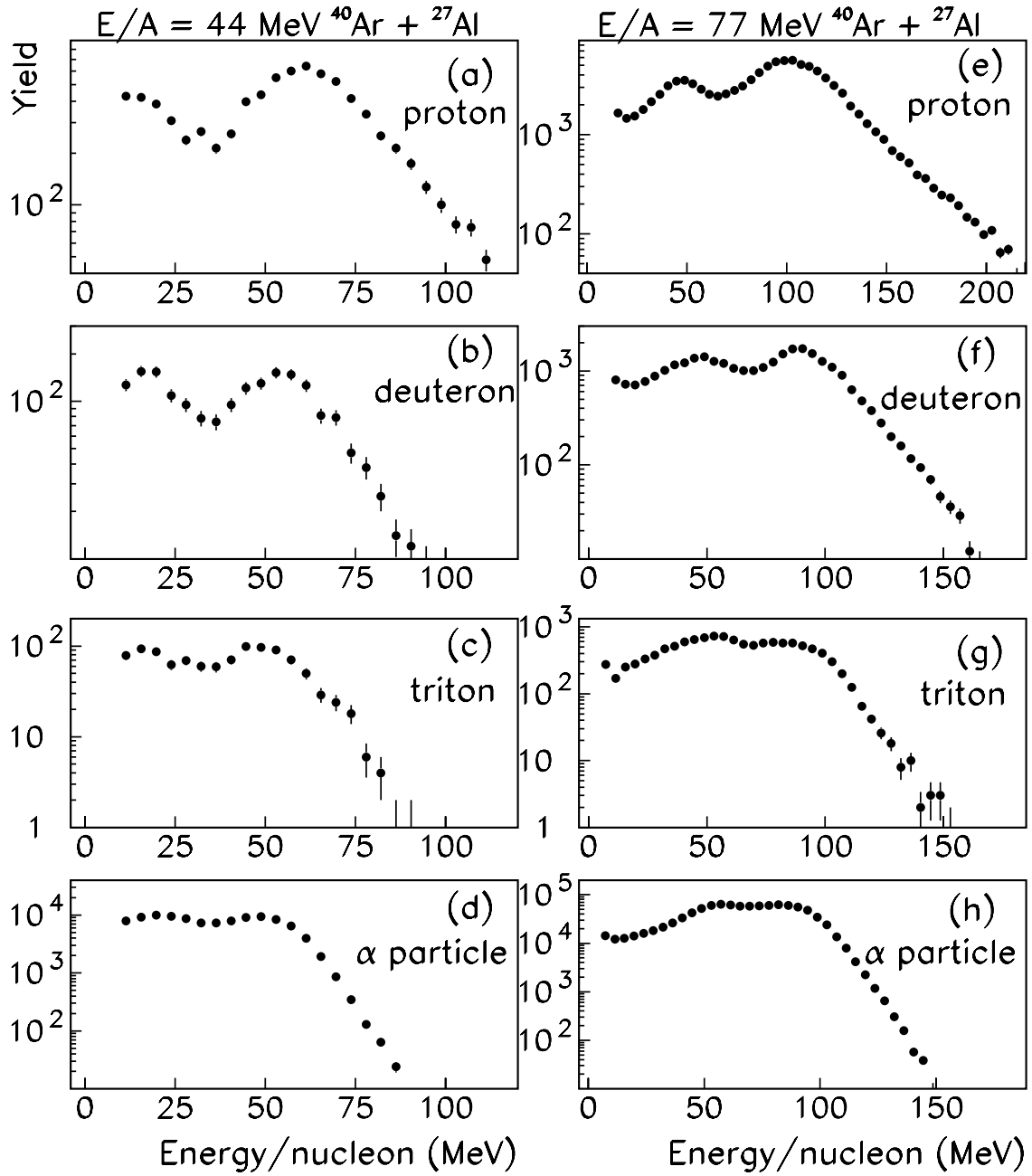


Fig. 1. From $E/A = 44$ MeV (left column) and 77 MeV (right column) $^{40}\text{Ar} + ^{27}\text{Al}$ collisions, distributions of the laboratory kinetic energy/nucleon of the LCPs detected at $0.7^\circ \leq \theta_{lab} \leq 7^\circ$. At a given bombarding energy, all the spectra have the same (arbitrary) normalization.

come from recoil effects. Finally, a reduced dumb-bell shape may be caused by an enhanced contribution of non-PLF decay mechanisms (such as intermediate velocity source emission and secondary emission from the decay of highly excited primary fragments) for t and α emission. Indeed, the average relative intensity of intermediate

velocity source emission is larger for α -particles than for protons, as demonstrated in Ref. [18] for the $E/A = 44$ MeV $^{40}\text{Ar} + ^{27}\text{Al}$ reaction.

4) The dumb-bell shape associated with PLF decay is slightly more pronounced at $E/A = 44$ MeV than at 77 MeV. This is partly explained by the fact that the Coulomb push becomes relatively less important at 77 MeV, as compared to the boost from the source system to the laboratory system. In addition, it may be partly explained by an enhanced contribution of non-PLF decay mechanisms at the higher energy (intermediate velocity source emission and secondary decay) [18,24].

5) The yield of α -particles is rather large in this forward angular range. Speculations on the origin of these copious α -particles have been discussed in Refs. [17,18]. It could be due to the production in the reaction of excited light ions, and/or to the α structure of the two interacting nuclei [25].

4 Two-particle correlation functions

The experimental correlation function is constructed by dividing the coincidence yield, N_c , by the yield of uncorrelated events, N_{nc} ,

$$C(\vec{q}, \vec{P}_{tot}) = k \frac{N_c(\vec{q}, \vec{P}_{tot})}{N_{nc}(\vec{q}, \vec{P}_{tot})}. \quad (1)$$

$\vec{q} = \mu(\vec{p}_1/m_1 - \vec{p}_2/m_2)$ is the relative momentum, μ is the reduced mass, and $\vec{P}_{tot} = \vec{p}_1 + \vec{p}_2$ is the total momentum of the particle pair. In the following, an implicit integration over the six variables \vec{q} and \vec{P}_{tot} is performed. The correlation function is normalized to unity at large values of q , where no correlations are expected. The background yield, N_{nc} , can be constructed either from the product of the singles distributions [26] or with the so-called “event-mixing” technique [27], combining particles from different events. We have verified that, for the present data set, the two techniques yield the same results, within the experimental uncertainty. Thus, we have chosen to utilize the singles technique.

In the present analysis, only particles with energy/nucleon larger than a value slightly below the beam energy have been utilized to construct $C(q)$. This is because combining particles from both peaks of the dumb-bell shaped energy distributions (Fig. 1), introduces correlations other than two-body final state interactions and/or quantum symmetrization effects. These unwanted correlations most likely originate from a mixing of sources with different velocities. For more details, see Ref. [24]. By applying this energy cut, the contribution from the PLF source relative to other sources is enhanced, while the statistics and the accessible range of relative momenta are reduced. Nevertheless, thanks to the small angular separation between the centers of

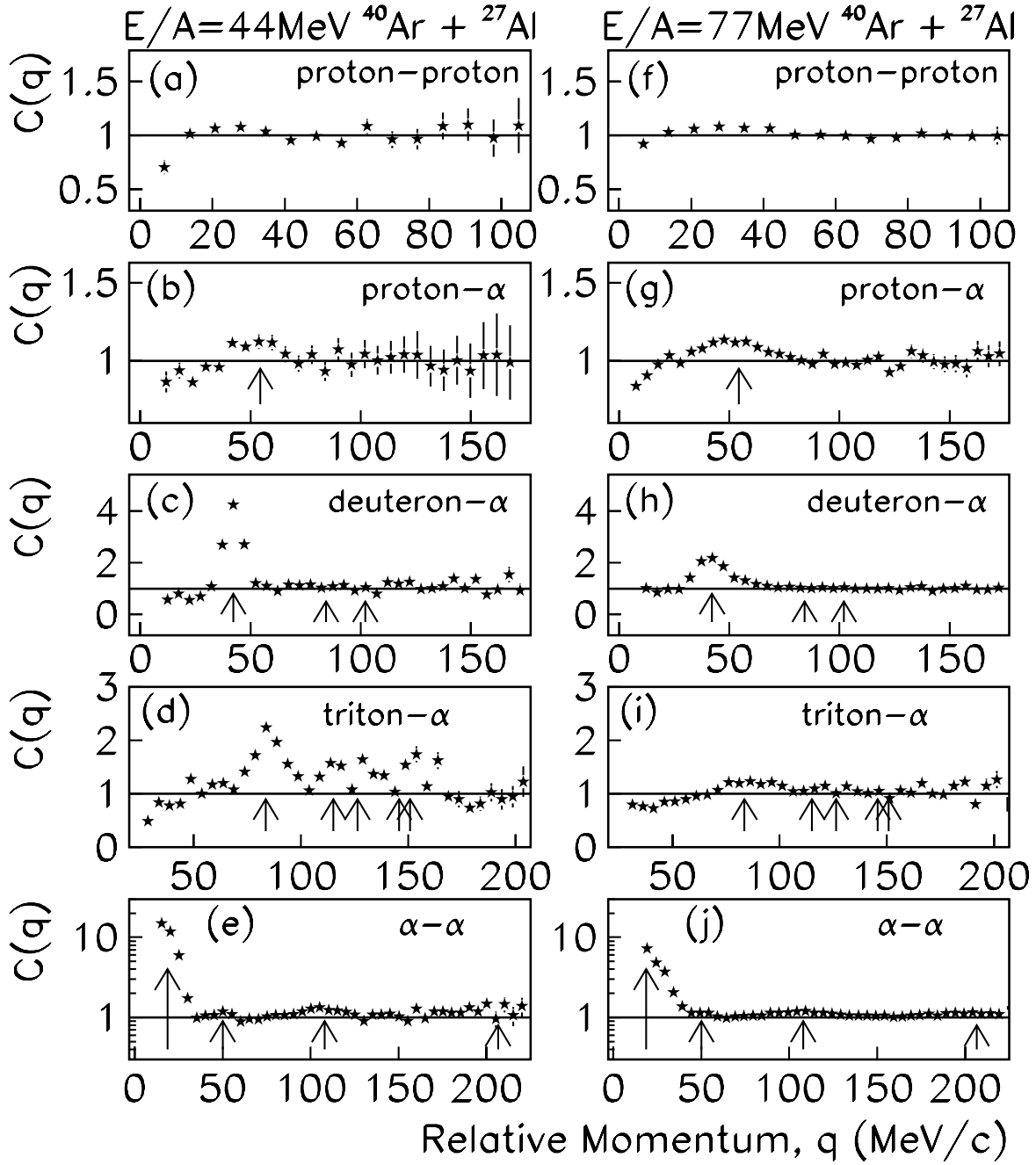


Fig. 2. From $E/A = 44$ (left column) and 77 (right column) MeV $^{40}\text{Ar} + ^{27}\text{Al}$ collisions, pp [panels (a,f)], $p\alpha$ [panels (b,g)], $d\alpha$ [panels (c,h)], $t\alpha$ [panels (d,i)], and $\alpha\alpha$ [panels (e,j)] correlation functions. The position of expected resonance peaks is indicated by the arrows.

two adjacent detectors ($\approx 1.5^\circ$), the region of small relative momenta (where interesting signatures of final state interactions and antisymmetrization effects appear) is still populated.

Before we proceed to analyze the experimental results, we would like to point out that, for those correlation functions characterized by final state interaction with resonances, the resonance peaks may a priori have two different origins [28,29]:

- i) From processes where a “preformed fragment” decays into the two measured particles. If the secondary decay of a specific fragment produces two particles that are measured in coincidence (like in e.g. ${}^8\text{Be} \rightarrow \alpha + \alpha$ or ${}^6\text{Li} \rightarrow \alpha + d$), the decay will give rise to a resonance peak in the corresponding correlation function.
- ii) From interactions between independently emitted particles. De-excitation of the PLF and secondary decay of excited fragments may produce single particles that interact with particles emitted by other sources. The relative distance for such pairs will be large (due to both space and time) and they will interact weakly. This means that they will give rise to correlation effects mainly at small relative momenta [30].

Figure 2 presents the correlation functions of particle pairs measured in the $E/A = 44$ and 77 MeV ${}^{40}\text{Ar} + {}^{27}\text{Al}$ experiments. The events are selected with the conditions described in Sec. 2. The low energy thresholds are set to 35 MeV/nucleon for the $E/A = 44$ MeV data, and 65 MeV/nucleon for the $E/A = 77$ MeV data, for the reasons discussed above and in Ref. [24].

The pp correlation function (normalized in the relative momentum region $q = 80$ – 100 MeV/c) is shown in Figs. 2(a,f). This result was already presented in Ref. [24]. It exhibits a shallow maximum at $q \approx 20$ MeV/c, caused by the attractive s -wave interaction between the two protons. The maximum at 20 MeV/c may be seen as the resonance peak from the decay of the particle unstable ${}^2\text{He}$. The minimum at $q \rightarrow 0$ MeV/c is due to the interplay between quantum antisymmetrization effects and final state Coulomb repulsion between the two protons [31]. The very weak peak at 20 MeV/c indicates that proton emission occurs on a long time scale [31].

The $p\alpha$ correlation function (normalized in the relative momentum region $q = 100$ – 150 MeV/c) is shown in Figs. 2(b,g). The broad peak at $q \approx 54$ MeV/c is due to the unbound ground state of ${}^5\text{Li}$ (1.69 MeV above the $p + \alpha$ threshold, $\Gamma_{cm} = 1.23$ MeV) [32]. Most probably, the bump contains additional contributions from a background of p and α -particles emitted independently from source de-excitation (the large yields of p and α [17,18] enhance the probability that two such particles are emitted close enough in time that they will experience strong final state interaction).

The very similar behavior of the two pp and $p\alpha$ correlation functions at $E/A = 44$ and 77 MeV, indicates that the characteristics of PLF proton and α -particle emission are rather independent of the beam energy. As demonstrated by the statistical calculations of Ref. [33], different emitted particles from the PLF are sensitive to different portions of the PLF de-excitation cascade. Because of the Coulomb barrier and of the binding energy relative to the available excitation of the PLF, the emission time distribution of protons and α -particles is expected to be rather flat. In the calculations of [33], the emission time distribution exhibited by α -particles is found to decrease

by only a factor of 3 over the time interval of 150 fm/c, while other particles (e.g. tritons) exhibit steeper distributions, decreasing more than one order of magnitude in the same time interval. Thus, protons and α -particles are expected to sample the end of PLF de-excitation cascade, and this effect is expected to be approximately the same at 44 and at 77 A MeV. In addition, there might be a large background of independently emitted protons and α -particles from secondary decay of excited fragments, also probing the long time scale.

The $d\alpha$ correlation function (normalized in the relative momentum region $q = 110$ – 150 MeV/c) is shown in Figs. 2(c,h). It is governed by the strong resonance at $q \approx 42.2$ MeV/c, due to the 2.186 MeV ($\Gamma_{cm} = 0.024$ MeV) excited state of ${}^6\text{Li}$ [32]. This resonance peak reaches the value $C(q \approx 42) \approx 4.2$ at $E/A = 44$ MeV, as compared to $C(q \approx 42) \approx 2.2$ at $E/A = 77$ MeV. The resonances expected at $q \approx 84$ MeV/c and 102 MeV/c (from the overlap of the ${}^6\text{Li}$ excited states at 4.31 MeV, $\Gamma_{cm} = 1.30$ MeV, and 5.65 MeV, $\Gamma_{cm} = 1.50$ MeV) [32] are hardly seen in the data.

The $t\alpha$ correlation function (normalized in the relative momentum region $q = 180$ – 200 MeV/c) is shown in Figs. 2(d,i). Because of experimental difficulties in the identification of low energy tritons and α -particles, the $t\alpha$ correlation function is presented in the region $q > 30$ MeV/c [the x-axis scale is zero-suppressed in Figs. 2(d,i)]. The $t\alpha$ correlation function is characterized by a maximum at $q \approx 83.6$ MeV/c, due to the 4.652 MeV ($\Gamma_{cm} = 0.069$ MeV) excited state of ${}^7\text{Li}$ [32]. This resonance peak reaches the value $C(q \approx 83) \approx 2.1$ at $E/A = 44$ MeV, as compared to $C(q \approx 83) \approx 1.2$ at $E/A = 77$ MeV. Other excited states of ${}^7\text{Li}$ that decay into $t\alpha$ are at 6.60 MeV ($\Gamma_{cm} = 0.918$ MeV), 7.45 MeV ($\Gamma_{cm} = 0.080$ MeV), 9.09 MeV ($\Gamma_{cm} = 2.752$ MeV), and 9.57 MeV ($\Gamma_{cm} = 0.437$ MeV) [32]. The corresponding resonances, expected at $q = 115.1$, 126.3, 145.7, and 150.8 MeV/c, are visible in the $E/A = 44$ MeV data.

Finally, the $\alpha\alpha$ correlation function, (normalized in the relative momentum region $q = 140$ – 180 MeV/c) is shown in Figs. 2(e,j), in semi-logarithmic scale. This result was already presented in Ref. [24]. This correlation function is dominated by the decay of the particle unstable ground state of ${}^8\text{Be}$ ($\Gamma_{cm} = 5.57$ eV) at $q = 18.6$ MeV/c [34]. This resonance peak reaches the value $C(q \approx 18) \approx 13.5$ at $E/A = 44$ MeV, and $C(q \approx 18) \approx 8.5$ at $E/A = 77$ MeV. The decay of the 2.43 MeV excited state of ${}^9\text{Be}$ ($\Gamma_{cm} = 0.78$ keV) into the undetected neutron and the unstable ${}^8\text{Be}$ ground-state, as well as the decay of the 3.03 MeV ($\Gamma_{cm} = 1.51$ MeV) and 11.35 MeV ($\Gamma_{cm} = 3.5$ MeV) excited states of ${}^8\text{Be}$ [34], lead to resonance peaks at $q \approx 50$, 108, and 206 MeV/c, more clearly visible in the $E/A = 44$ MeV data.

In summary, comparing the results from the two beam energies, we have seen that the resonance peaks are more pronounced at $E/A = 44$ MeV than at 77 MeV. The effect is largest for the $d\alpha$ correlation function (ratio of main peaks is 1.90), followed by the $t\alpha$ (ratio of main peaks is 1.75) and the $\alpha\alpha$ (ratio of main peaks is 1.59). This indicates that at $E/A = 77$ MeV there is a larger yield of uncorrelated light particles (in particular d and t) as compared to heavy fragments (in particular ${}^8\text{Be}$,

${}^7\text{Li}$, and ${}^6\text{Li}$). This finding is in agreement with the results from the analysis of the particle-velocity-gated correlation functions, presented in the next section.

5 Particle emission time sequence

Correlation functions of non-identical particles can be utilized to provide information about the order of emission of the different particles [35]. To this end, particle-velocity-gated correlation functions are constructed [19,20].

For non-identical particles, say a and b , we construct the correlation functions $C_a(q)$, gated on pairs with $v_a > v_b$, and $C_b(q)$, gated on pairs with $v_b > v_a$. If particle a is emitted later (earlier) than particle b , the ratio C_a/C_b will show a peak (dip) in the region of q where there is a correlation, and a dip (peak) in the region of q where there is an anticorrelation. The particle velocities are calculated in the frame of the PLF. A single normalization constant, calculated from the ungated correlation function, is utilized for both C_a and C_b [20].

The $p\alpha$, $d\alpha$, and $t\alpha$ correlation functions are characterized by final state interaction with resonances. If the two particles are emitted independently, the velocity-gated correlation functions contain information on the time sequence, but this is not the case if the two particles originate from the decay of a “preformed fragment”. In the latter case, the two particle velocities are determined by momentum conservation, and, in the rest system of the decaying fragment, the lightest particle will always get the highest velocity. Therefore, the expected behavior for particle pairs coming from a two-body decay of a decaying fragment is the following: the velocity-gated correlation function, obtained with the condition that the lightest particle has the largest velocity, should exhibit the strongest correlation or anticorrelation. Therefore, when we, in some cases, observe the opposite behavior (namely that the gate where *the heaviest* particle has the largest velocity leads to a stronger correlation or anticorrelation) we can reliably conclude that this behavior is dominated by a mechanism different than two-body decay. We attribute this effect to the interaction of independently emitted particles, and, in this case, we use the velocity-gated correlation function to obtain information on the time sequence of the independently emitted particles [36].

The particle-velocity-gated $p\alpha$ correlation function is shown in Fig. 3. In the relative momentum region dominated by the two-body decay of ${}^5\text{Li}$ ($q \approx 54$ MeV/c) the enhancement of $C_p(v_p > v_\alpha)$ over $C_\alpha(v_\alpha > v_p)$, expected from momentum conservation, is not observed. This is a first indication that the behavior of the $p\alpha$ correlation function is dominated by a background of independently emitted pairs. The emission chronology can be deduced from the behavior at $q < 30$ MeV/c, where there are no resonant states that directly lead to the formation of $p\alpha$ pairs, and where the $p\alpha$ correlation function displays an anticorrelation ([37] and Fig. 2). The fact that pairs with $v_p > v_\alpha$ (contributing to C_p) interact more strongly (stronger anticorrelation at

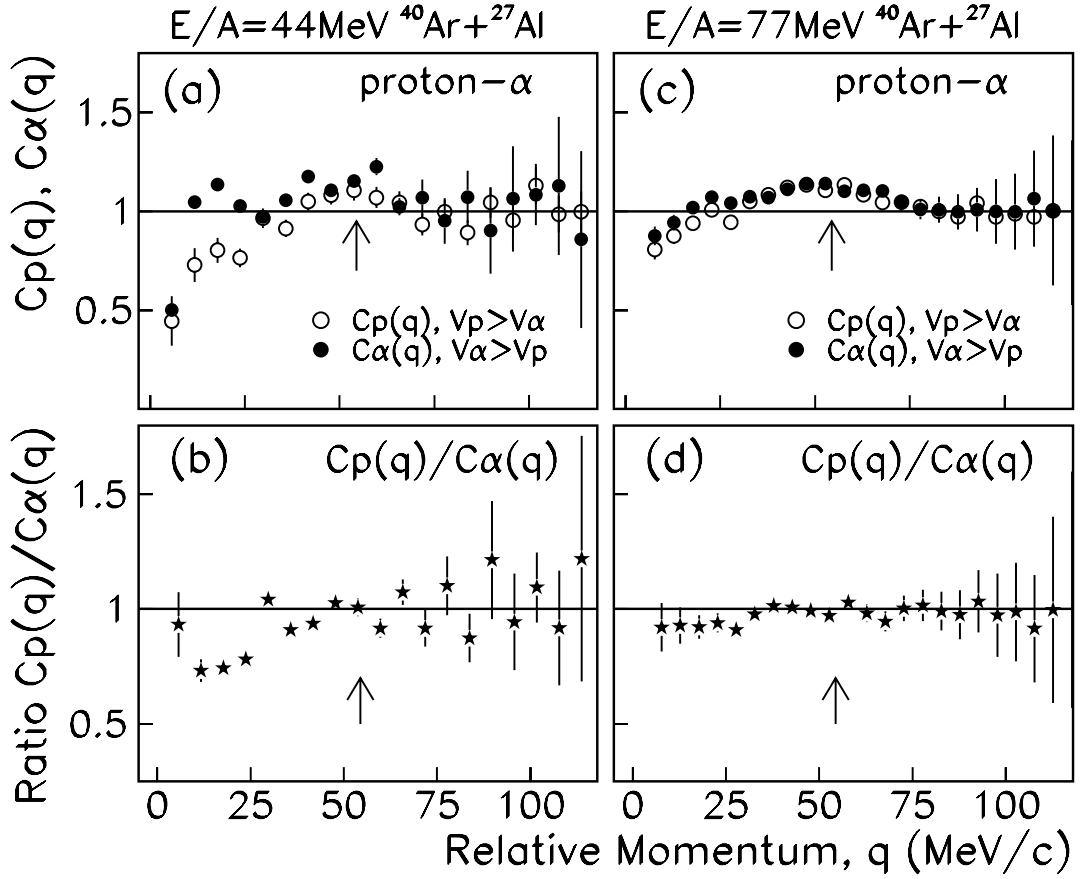


Fig. 3. From $E/A = 44$ MeV (left column) and 77 MeV (right column) $^{40}\text{Ar} + ^{27}\text{Al}$ collisions, upper panels: particle-velocity-gated (filled and open circles) $p\alpha$ correlation functions; lower panels: the ratio of the particle-velocity-gated correlation functions.

$q < 30$ MeV/c) indicates that, on average, protons are emitted later than α -particles. Inspection of the C_p/C_α ratios (Fig. 3, lower panels) reveals that the deduced $p\alpha$ emission chronology is qualitatively similar for the two beam energies.

The particle-velocity-gated $d\alpha$ correlation function is shown in Fig. 4. For $d\alpha$ pairs, the behavior of the C_d/C_α ratio (Fig. 4 lower panels) is of delicate interpretation, being dominated by the two-body resonance decays of ^6Li . For $d\alpha$ pairs originating from the two-body decay of ^6Li excited states, the inequality $v_d > v_\alpha$ should hold in the ^6Li rest system (due to momentum conservation), leading to an enhancement of the C_d correlation function in the PLF system at $q \approx 42.2$ MeV/c (as discussed above). The experimental data display such an enhancement of the C_d correlation function in the $E/A = 44$ MeV measurement [Fig. 4(a)], therefore it is difficult to deduce the emission chronology in this case. One has to rely on the behavior of the particle-velocity-gated correlation function at $q < 30$ MeV/c, where there are no resonant states and where the $d\alpha$ correlation function displays an anticorrelation [37].

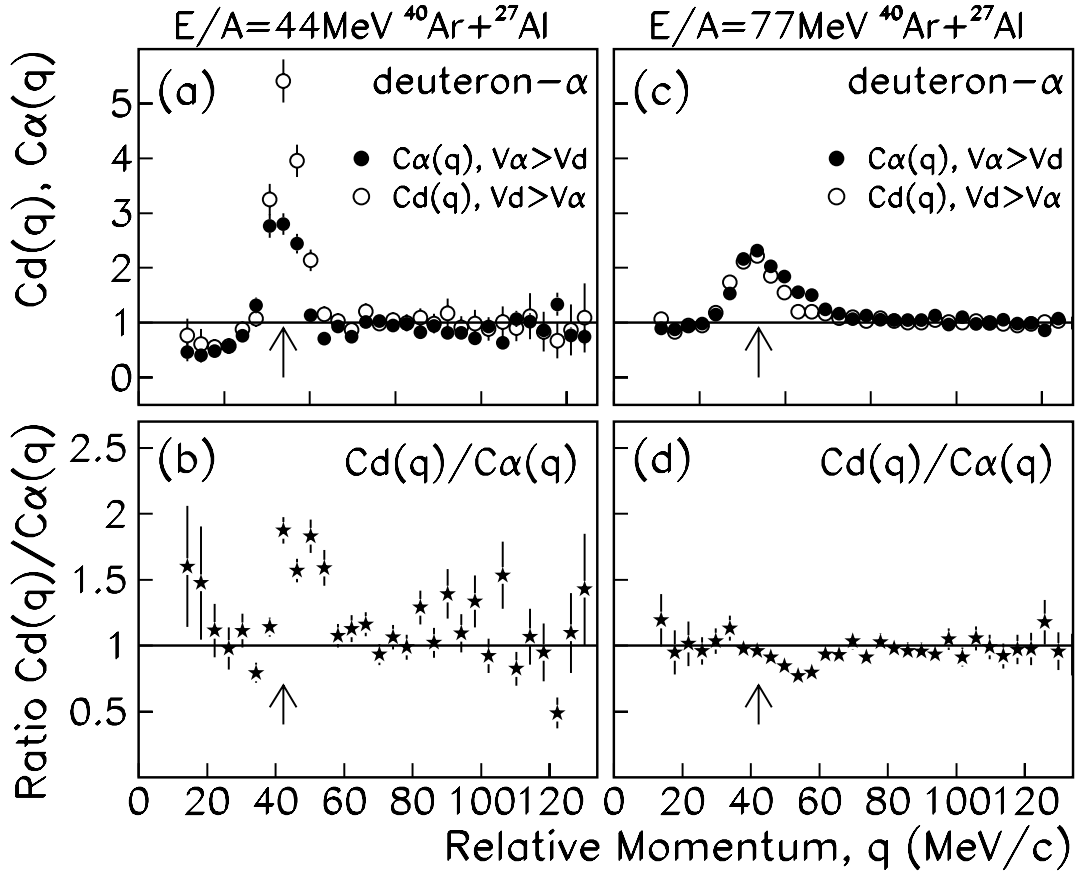


Fig. 4. From $E/A = 44$ MeV (left column) and 77 MeV (right column) $^{40}\text{Ar} + ^{27}\text{Al}$ collisions, upper panels: particle-velocity-gated (filled and open circles) $d\alpha$ correlation functions; lower panels: the ratio of the particle-velocity-gated correlation functions.

However, the statistics is very low in this region. The fact that pairs with $v_\alpha > v_d$ interact more strongly [the ratio C_d/C_α is larger than unity in this anticorrelation region, Fig. 4(b)] gives an indication that deuterons are, on average, emitted earlier than α -particles.

The kinematical signature of two-body resonance decay is much weaker in the $E/A = 77$ MeV $d\alpha$ data. The enhancement of C_d over C_α is not observed [Fig. 4(c)], and the ratio C_d/C_α is close to unity at $q \approx 42.2$ MeV/c [Fig. 4(d)], while it exhibits a dip in the region $q \approx 40\text{--}70$ MeV/c, where the $d\alpha$ correlation function displays a correlation [37]. Such a dip cannot originate from the decay of ^6Li (for momentum conservation reasons, see previous discussion). This indicates that the yield of $d\alpha$ pairs measured at $E/A = 77$ MeV is largely contributed by pairs that are not emitted by the decay of ^6Li excited states, but that are emitted independently from PLF or secondary fragment decay. The result of the emission time chronology for these pairs, as deduced from the dip in the C_d/C_α ratio at $q \approx 40\text{--}70$ MeV/c, is that deuterons are, on average,

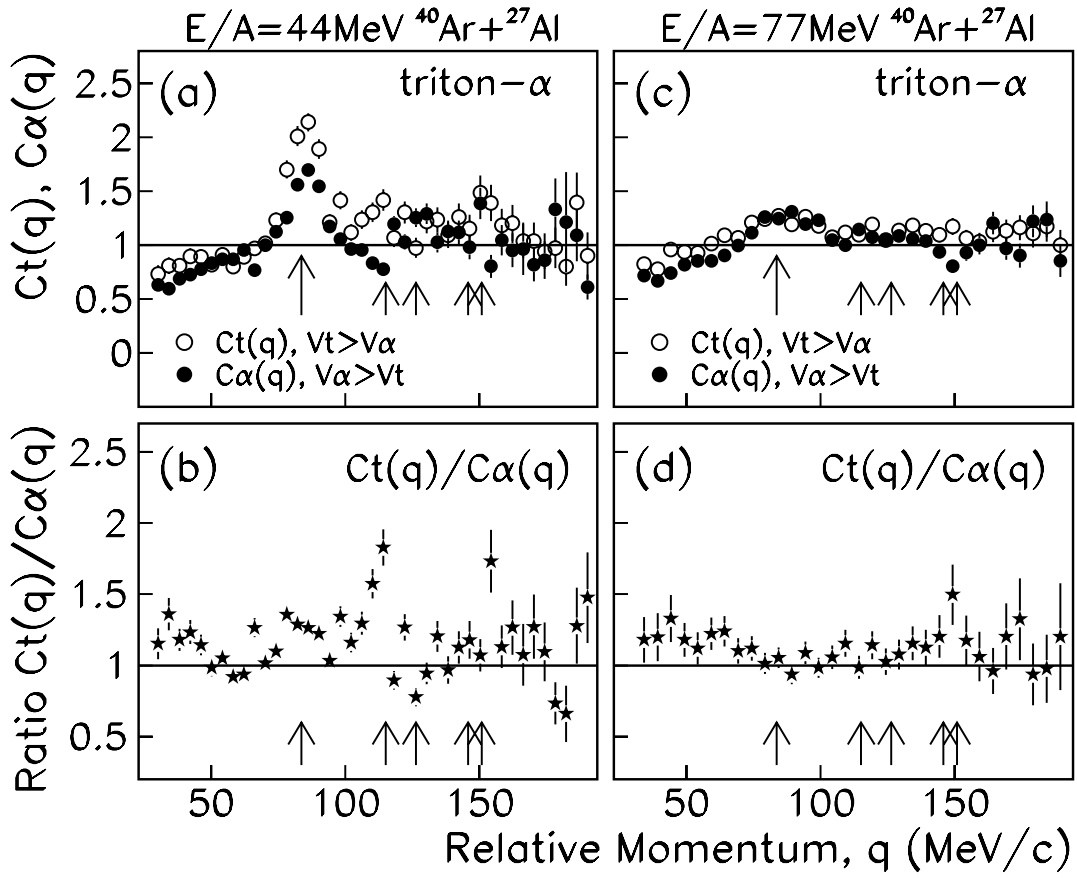


Fig. 5. From $E/A = 44$ MeV (left column) and 77 MeV (right column) $^{40}\text{Ar} + ^{27}\text{Al}$ collisions, upper panels: particle-velocity-gated (filled and open circles) $t\alpha$ correlation functions; lower panels: the ratio of the particle-velocity-gated correlation functions.

emitted earlier than α -particles.

Finally, the particle-velocity-gated $t\alpha$ correlation function is shown in Fig. 5. Also in this case, the resonance peaks are more pronounced at $E/A = 44$ MeV than at 77 MeV. For the $E/A = 44$ MeV data, the behavior of the C_t/C_α ratio at $q > 70$ MeV/c is dominated by the kinematical signature of these two-body decays. Due to momentum conservation, the inequality $v_t > v_\alpha$ dominates in the PLF frame for $t\alpha$ pairs originating from two-body decays, leading to an enhancement of the particle-velocity-gated correlation function C_t . The emission chronology is deduced from the behavior of the particle-velocity-gated correlation function at $q < 70$ MeV/c, where there are no resonant states and the $t\alpha$ correlation function displays an anticorrelation ([37] and Fig. 2). For both $E/A = 44$ and 77 MeV data, the ratio C_t/C_α (Fig. 5, lower panels) is larger than unity in this anticorrelation region, indicating that tritons are, on average, emitted earlier than α -particles.

In summary, the results from the analysis of particle-velocity-gated correlation functions indicate that, at both bombarding energies, α -particles have an average emission time shorter than protons, but longer than deuterons and tritons. As we have pointed out, because of the dominating behavior of the resonant states at $E/A = 44$ MeV (discussed in Sec. 4), the study of the particle emission chronology from the analysis of particle-velocity-gated $d\alpha$ and $t\alpha$ correlation functions is rather delicate at $E/A = 44$ MeV. Nevertheless, the indications from the resonance-free, low- q regions, support a particle emission time sequence in agreement with that deduced at the higher bombarding energy.

6 Summary and conclusions

Single particle energy spectra and two-particle correlation functions have been measured simultaneously and in coincidence with forward emitted fragments from $E/A = 44$ and 77 MeV $^{40}\text{Ar} + ^{27}\text{Al}$ reactions. The measurements have been performed at very forward angles, $0.7^\circ \leq \theta_{lab} \leq 7^\circ$, with the aim to study the characteristics of de-excitation of the PLF source.

A signature of PLF decay is found in the energy spectra of protons, deuterons, tritons and α -particles. These are characterized by a dumb-bell peak structure, typical of particles emitted isotropically by a PLF, with a velocity component either parallel to PLF movement (higher energy peak) or antiparallel (lower energy peak). In order to exclude correlations other than final state interactions and quantum symmetrization effects, only particles from the higher energy peak have been considered, thus enhancing PLF emission [24].

The correlation functions dominated by resonances ($d\alpha$, $t\alpha$, and $\alpha\alpha$) consistently display higher resonance peaks at $E/A = 44$ MeV than at 77 MeV. This indicates that the relative abundance of light particles (in particular d and t) as compared to heavy fragments (in particular ^8Be , ^7Li , and ^6Li) is larger at $E/A = 77$ MeV than at $E/A = 44$ MeV.

The proton-proton correlation function indicates a lack of final state interaction, typical of particles emitted by a long-lived source. This feature is found in both $E/A = 44$ and 77 MeV data, pointing to characteristics of the PLF emission source that are rather independent of the beam energy, for what concerns the long-time tail of the PLF de-excitation chain, probed by protons.

The correlation functions of non-identical particle pairs have been utilized to deduce the particle emission time sequence in a model independent way, based on particle-velocity-gated correlation functions. For correlation functions characterized by final state interaction with resonances, care has to be taken to deduce the information on the emission time sequence from independently emitted particles (discarding particles

coming from resonance decays). This can be achieved in two ways:

- i) With particle-velocity gates in regions of relative momentum where there are no resonant states that directly lead to the formation of the particle pair.
- ii) With particle-velocity gates in regions of the relative momentum where there is a resonance peak, but the peak is not dominated by particles coming from resonance decay. When a resonance peak is dominated by particles coming from resonance decay, momentum conservation implies that the correlation is stronger for the particle-velocity-gated correlation function with the velocity of the lighter particle larger than the velocity of the heavier particle. Violation of this condition is a signature that the peak is dominated by independently emitted particles, and can thus be utilized to deduce the particle emission time sequence.

The results from this analysis indicate that, at both bombarding energies, α -particles have an average emission time shorter than protons but longer than deuterons and tritons. This finding is consistent with the emerging picture of a PLF that is de-excited by early emission of tritons and deuterons (with larger yields for the higher beam energy), followed by α -particles and protons. Indeed, because of the Coulomb barrier and of the binding energy relative to the available excitation of the PLF, the emission time distribution of protons and α -particles is expected to be rather flat [33].

The deduced LCP emission time sequence appears to be in qualitative agreement with previous experimental findings from three-moving source fits to single particle energy spectra in $E/A = 44$ and 60 MeV $^{40}\text{Ar} + ^{27}\text{Al}$ collisions [17,18]. The PLF source temperatures deduced from these fits were found to be lowest for protons (3.6 MeV at 44 A MeV, 4.9 MeV at 60 A MeV), followed by α -particles (4.7 MeV at 44 A MeV, 6.9 MeV at 60 A MeV), then deuterons (5.0 MeV at 44 A MeV, 8.5 MeV at 60 A MeV) and tritons (5.9 MeV at 44 A MeV, 8.5 MeV at 60 A MeV). These findings were interpreted as a suggestion that an important fraction of α -particles is emitted in the final stage of the collision. Different hypotheses have been advanced to explain this late emission of α -particles, including the concept of α -clusterization of nuclei [25] and the production of α -particles by secondary decay of light fragments produced in the collisions [38,39].

The qualitative interpretations of the data analysis given in the present paper should be supported by comparisons to statistical model calculations. Such model comparisons will be presented in a forthcoming paper [36].

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