

Implications of two-body fragment decay for the interpretation of emission chronology from velocity-gated correlation functions

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From velocity-gated small-angle correlation functions, the emission chronology can be deduced for nonidentical particles, if the emission is independent. This is not the case for nonidentical particles that originate from two-body decay of fragments. Experimental results may contain contributions from both independent emission and two-body decay, so care is needed in interpreting the velocity-gated correlation functions. It is shown that in some special cases, it is still possible to deduce the emission chronology, even if there is a contribution from two-body decay.

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I. INTRODUCTION

Understanding the different origins of emission and the emission time sequence of different particles is a major challenge of intermediate-energy heavy ion collisions. For more than 20 years, two-particle intensity interferometry has been used as a probe, yielding convoluted space-time information that, however, is difficult to disentangle [1–4]. This is because of the presence of multiple sources and the competition of nonequilibrium emission processes with equilibrium relaxation modes, leading to a broad range of origins of the measured particles [5–13]. It is the purpose of this paper to discuss some of the assumptions made when inferring emission chronology from velocity-gated experimental correlation functions.

Particles emitted in nuclear collisions may interact with each other after the emission. This final state interaction causes the population in phase space to be altered, an effect that can be observed by the small-angle two-particle correlation function. The proximity in space and time of the interacting particles influences the strength of the final state interactions, and hence the size of the correlations seen in the correlation function $C(q)$, where $q \equiv \mu|\mathbf{p}_1/m_1 - \mathbf{p}_2/m_2|$ is the relative momentum and $\mu = m_1 m_2 / (m_1 + m_2)$ is the reduced mass. Correlation functions constructed from experimental data, therefore, contains information of the space-time characteristics of the emitting source. Experimentally, the correlation function is constructed by dividing the coincidence yield by the yield of noncorrelated events, normalized to unity at large values of relative momentum, where no correlations are expected. Often, much of the space-time information contained in this six-dimensional observable is lost because of implicit experimental integrations over some of the dimensions in the relative and total momenta. When statistics are high enough, some of the information can be recovered by applying directional cuts [14] and total-momentum or energy gates [2]. Furthermore, for nonidentical particle correlations, it is possible to apply particle-velocity gates and infer the emission chronology of the different particles [15–20].

Velocity-gated correlation functions of nonidentical particles is a very powerful method because it is model independent. However, some critical assumptions are made that may not always be fulfilled depending on the reaction scenario and selection of emitted particles. For the method to work, the particle velocities should be obtained in the frame of the emitting source. The source velocity may not always be a well-defined quantity, because of the implicit integration over a limited range of impact parameters. In Sec. III, we investigate in some detail the consequences of uncertainties in the source velocity. Another crucial assumption for extracting emission chronology from the velocity-gated correlation functions is that the nonidentical particles must be emitted *independently* by the excited source. If they instead originate from the two-body decay of a fragment, their respective velocity is determined solely by energy and momentum conservation, and they do not carry any useful information on the emission time. In Sec. IV, we investigate under which conditions the emission chronology may be inferred, when particles originate both from independent emission from a (large) source and from two-body decay of fragments.

II. SPACE-TIME CHARACTERIZATION

Normally, particles originating from a specific source are emitted at different rates during the time interval of emission, leading to a specific time distribution for the source. If a two-particle correlation function could be constructed from particles emitted from a single source and if the spatial distribution would be known, then the shape of the correlation function would yield information on the shape of the time distribution.¹ Normally, the spatial distributions are not known. To interpret the experimental results, source models containing some assumption on the spatial and temporal distributions are often used. The shape of these distributions can, to some extent,

¹Refs. [11,21–24] discuss the relation between the shape of the correlation function and the shape of the source function. If the spatial part of the source is known, the shape relation in Refs. [11,21–24] is directly applicable to the time distribution.

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be varied by varying parameters of the model. The best-fit parameters then represent the average emission point and average emission time, though it should be remembered that such average values are model dependent. In the experimental data, the situation is much more complex, since it is never possible to completely isolate one source from other sources present during the reaction. The contribution from several sources leads to a complex total time distribution.

The term *emission chronology* is usually used to denote a difference in the *average* emission time between two particle types. The difference in the average emission times may be small compared with the width of the emission time distributions. A difference in the average emission times, extracted from experimental data, may have different origins, depending on where the particles that are included in the observables are coming from. Possible origins may be the following:

- (i) A shift of two similar time distributions. This shift could be due to the nuclear interaction. For systems with an exotic isospin composition, the symmetry interaction could cause the emission time of neutrons and protons to be different.
- (ii) A different width for two otherwise quite similar time distributions. For an equilibrated source, differences in the Coulomb barrier for different particles could lead to different widths of the time distributions.
- (iii) Different relative weights of several sources. The abundance of emitted neutrons and protons from an intermediate velocity source, and nonequilibrated residues, could be different because of the isospin composition of the systems.

When interpreting experimental data, it is important to be aware of different possible origins of different average emission times in order to make the correct conclusions. Different origins can be enhanced or suppressed by applying different gates and conditions on the observables.

The emission chronology between two particle types (e.g., neutrons and protons) can, under certain conditions, be determined from identical particle correlation functions (e.g., neutron-neutron and proton-proton). If it is valid to assume that both particle types are emitted from the same spatial region, a model fit to the experimental data will yield an average emission time for each particle type. By comparing these average emission times, an emission chronology can be inferred [25]. The drawback of this method is that the results are sensitive to the assumption of emission from the same spatial region. Furthermore, the extracted average emission times are model dependent, since the average emission times depend on the shape of the (spatial and) temporal distributions assumed by the specific source model.

III. EMISSION CHRONOLOGY FROM NONIDENTICAL PARTICLE CORRELATIONS

Model-independent information on the emission chronology of two particle types (e.g., neutrons and protons) can be obtained from nonidentical particle correlation functions (e.g.,

neutron-proton). A technique was first suggested for charged particle pairs, based on comparison of the velocity difference spectra with trajectory calculations [26–28]. The technique was extended to any kind of interacting, nonidentical particles by applying energy or velocity gates and proposed for particle pairs such as pd and np [15], $p\pi$ [29], and K^+K^- [30].

A. Particle-velocity-gated correlation functions

The basic idea of velocity-gated correlation functions of nonidentical particles [16–18] is that if there is an average time difference in the emission times of two particles types, there will also be a difference in the average distance between the particles for particle pairs selected with the condition $v_1 > v_2$ as compared to the pairs selected with the complementary condition $v_1 < v_2$. It is obvious that in the class $v_1 > v_2$, the average velocity of particle 1 will be higher than in the complementary class $v_1 < v_2$. This means that if particle 1 is emitted first, it will, with the condition $v_1 > v_2$, on average travel a larger distance before the second particle is emitted than with the complementary condition. In this case, the condition $v_1 > v_2$ leads to on average larger distances (and weaker interactions) than the condition $v_1 < v_2$.

The effect can be easily seen if one compares the correlation function C_1 , gated on pairs $v_1 > v_2$, with the correlation function C_2 , gated on pairs $v_1 < v_2$. Assuming that particle 1 is on average emitted first, the ratio C_1/C_2 will show a dip in the region of relative momentum where there is a correlation (attractive interaction) and a peak where there is an anticorrelation (repulsive interaction). Furthermore, the ratio C_1/C_2 will approach unity for both $q \rightarrow 0$ (since the velocity difference of the two emitted particles is negligible) and $q \rightarrow \infty$ (since modifications of the two-particle phase space density arising from final state interactions are negligible). A single normalization constant calculated from the nongated correlation function is utilized for both C_1 and C_2 [16]. Note that while the height of the nongated and gated correlation functions depends on the normalization and therefore is sensitive to the statistics, the ratio of the velocity-gated correlation is not sensitive to the normalization, since the common normalization constant cancels out.

The exact location of the peak and/or dip in the ratio depends on the source and in particular on the origin of the difference in the average emission times. It should also be mentioned that it cannot be ruled out that the differences observed in velocity-gated correlation functions could have a spatial origin. However, such a correlation would then mean that there is a correlation between the spatial region where the particles are emitted and the particle velocities, *and* that this correlation is *different* for the two particle types used in the correlation functions. For heavy ion collisions at intermediate energies, such an explanation is clearly more unlikely than a difference in the average emission times.

B. Influence of “fast” and “slow” sources

Reference [11] states that when several emission sources are present in a nuclear reaction, the peak height in the pp -correlation function is affected both by the size of the

source with emission on a short time scale (“fast” component) and the admixture of particles emitted on a short and long (“slow” component) time scale. The width of the correlation function, on the other hand, does not depend on the admixture of fast and slow components, only on the size of the fast source. This is because the slow component contributes to the correlations only for very small relative momentum, below the pp -resonance peak. Thus care is needed when comparing peak heights of correlation functions obtained under different conditions, like total-momentum-gated correlation functions, since this could be due to a change of the fast and slow admixtures rather than a change in the (space-time) size of the fast source.

When applying velocity gates, however, the admixture of fast and slow gates should be very similar in the two complementary velocity gates. To see this, denote gate 1 as the gate when $v_1 > v_2$ and gate 2 as the gate when $v_2 > v_1$. For particle 1, it is clear that gate 1 will select more energetic particles than gate 2. It is therefore quite reasonable that gate 1 will contain more fast and less slow emitted particles of type 1 as compared to gate 2. However, the same reasoning can now be made for particle type 2, but with the gates reversed. Therefore, both gates contain approximately the same admixtures of fast and slow components. This means that any observed change in the peak heights will be because of different space-time sizes of the fast source.

Another issue from the findings in Ref. [11] is the extent to which the change in the width of the correlation function will affect the ratio of the velocity-gated correlation functions. In Fig. 2 of Ref. [11] the following features can be noted: (1) Both the height and the width of the pp -correlation peak depend on the source size; both grow with decreasing source size. (2) The variation of the width is approximately linear with the source size, while the peak height seems to grow approximately exponentially with decreasing source size. Feature (1) means that ² if C_1 probes a smaller space-time extent than C_2 , then the resonance peak of C_1 will have both a higher peak and a wider peak. Hence under the peak, the ratio C_1/C_2 will everywhere be larger than unity. Feature (2) means that the change in peak height will be much larger than the change in peak width. Thus, the ratio C_1/C_2 will be dominated by the change in peak heights.

C. Influence of the source velocity

The main uncertainty in the method of velocity-gated correlation functions comes from the uncertainty in the source velocity. This uncertainty originates mostly from an implicit impact parameter averaging in the experimental data. The range of selected impact parameters leads to a distribution of source velocities. In addition, the measured particles in the pair could have been emitted from different sources with

a relatively large difference in source velocity. By applying suitable conditions and gates on the experimental data, the fraction of such pairs should be low with respect to particles coming from the desired source.

If the velocity of the assumed source is different from the real source velocity, the calculated particle velocities in the assumed source frame will contain some error, and it may happen that the magnitude of the two particle velocities is interchanged as compared to the real source frame. In this section, we estimate the fraction of pairs that end up in the wrong gate, depending on the differences between the real and assumed source velocities.

Assume that particles 1 and 2 are emitted with velocities $\mathbf{v}_1^{(S)}$ and $\mathbf{v}_2^{(S)}$ from a source S . If the source has the velocity $\mathbf{v}_s^{(L)}$ in the laboratory system, the particle velocities in the laboratory system become

$$\mathbf{v}_i^{(L)} = \mathbf{v}_i^{(S)} + \mathbf{v}_s^{(L)}, \quad i = 1, 2. \quad (1)$$

If the velocity $\mathbf{u}_s^{(L)}$ is used to calculate the particle velocities in the source system, we get

$$\begin{aligned} \mathbf{u}_i^{(S)} &= \mathbf{v}_i^{(L)} - \mathbf{u}_s^{(L)} \\ &= \mathbf{v}_i^{(S)} + [\mathbf{v}_s^{(L)} - \mathbf{u}_s^{(L)}], \quad i = 1, 2. \end{aligned} \quad (2)$$

The condition $v_1^{(S)} > v_2^{(S)}$ can also be expressed $0 < [v_1^{(S)}]^2 - [v_2^{(S)}]^2$, and it is straightforward to show that

$$[u_1^{(S)}]^2 - [u_2^{(S)}]^2 = [v_1^{(S)}]^2 - [v_2^{(S)}]^2 + 2[\mathbf{v}_s^{(L)} - \mathbf{u}_s^{(L)}] \cdot \frac{\mathbf{q}}{\mu}. \quad (3)$$

The error of using the velocities u_i instead of the real velocities v_i can thus be estimated from Eq. (3). Noting that $[v_1^{(S)}]^2 - [v_2^{(S)}]^2 = [\mathbf{v}_1^{(S)} + \mathbf{v}_2^{(S)}] \cdot \mathbf{q}/\mu$, the expression shows that if a reasonably good source selection has been done, so that $|\mathbf{v}_s^{(L)} - \mathbf{u}_s^{(L)}|$ is small relative to $|\mathbf{v}_1^{(S)} + \mathbf{v}_2^{(S)}|$, the second term in the right hand side of Eq. (3) should be negligible. This is especially the case when the relative momentum increases, since $|\mathbf{v}_1^{(S)} + \mathbf{v}_2^{(S)}|$ increases with q for nonidentical particles.

As an example, we have made a simple simulation for the case of one proton and one α particle emitted from a source. We have assumed a Boltzmann distribution of the particle energies, with temperatures $T(p) = 6$ MeV and $T(\alpha) = 8$ MeV.³ The particles have been assumed to be emitted isotropically. The difference between the real source velocity and the assumed one has been taken normally distributed, with random direction. The result is presented in Fig. 1(a), where it is seen that the number of pairs attributed to the wrong velocity gate is around 5% for a realistic estimate of the uncertainty in the source velocity [see Fig. 1(b)]. The error becomes larger if the source velocities have a larger spread, but even for an unrealistically large uncertainty in the source

²We apply the results of Ref. [11] obtained for pp correlations for the case of correlations of nonidentical light charged particle correlations, since the cited features in Ref. [11] should be general for particles with a Coulomb repulsion and a strong attractive interaction.

³We have assumed that the α particle is emitted somewhat earlier than the proton [19], thus it has a higher average temperature. However, the assumption of different temperatures does not influence the conclusions of this section.

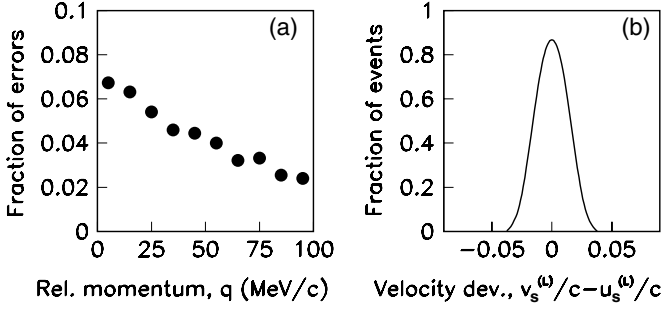


FIG. 1. Results from the simulation described in Sec. III C. (a) Fraction of pairs attributed to the wrong velocity gate due to the uncertainty in the assumed source velocity. (b) Used distribution of source velocities.

velocity, covering all possible velocities in the reaction, the fraction of wrongly attributed pairs is less than 25%.

The example indicates that for most cases, the error will be small, only a few percent. Nonetheless, this should be explicitly verified in each application of the method based on velocity-gated correlation functions.

IV. TWO-BODY DECAY FROM FRAGMENTS

A. Background

For those correlation functions characterized by final state interactions leading to resonances, the resonance peaks may *a priori* have two different origins [31–33]: (1) from interactions between independently emitted particles from a (large) source⁴ and (2) from processes where an unstable fragment formed in the reaction decays into the two measured particles (as in, e.g., ${}^8\text{Be} \rightarrow \alpha + \alpha$ or ${}^6\text{Li} \rightarrow \alpha + d$).

In the case of a fragment decaying into two nonidentical particles, the velocity of the two particles in the fragment rest frame is always such that the lighter particle has a higher velocity than the heavier particle. This follows from energy and momentum conservation in the decay. If we could construct a velocity-gated correlation function with all particles coming from two-body fragment decays and with their velocities calculated in the fragment frame, we would find all the pairs in the gate where the lighter fragment has a higher velocity, and none in the complementary gate. In Sec. IV C, we show that even if the particle velocities are calculated in another frame, more than 50% of the events from fragment decay will still be attributed to the gate where the lighter fragment has the higher velocity.

Any deviation from this behavior in experimental data would be due to particles from other sources than two-body fragment decays. Therefore, when in some cases it is observed

⁴That is, the two particles interact and thereby change their momenta in such a way that the relative momentum region under the resonance peak is populated, but the particles do *not* form a fragment that then in turn undergoes two-body decay. The latter process would not be distinguishable from two-body decay of fragments formed by other mechanisms in the reaction, corresponding to process (2) in the list.

that the gate where the *heaviest* particle has the highest velocity leads to a stronger correlation or anticorrelation than the complementary gate, it can reliably be concluded that this behavior is dominated by a mechanism different than two-body decay. In such cases, the effect may be attributed to the interaction of independently emitted particles, and the velocity-gated correlation function can be used to obtain information on the time sequence of the independently emitted particles (see, e.g., Ref. [19]).

B. Kinematics

Consider a fragment A_F with mass m_F decaying into two particles A_1 and A_2 , with masses m_1 and m_2 , $A_F \rightarrow A_1 + A_2$. Momentum conservation in fragment rest frame,

$$-\mathbf{p}_1 = \mathbf{p}_2 \equiv \mathbf{q}, \quad (4)$$

and energy conservation,

$$\begin{aligned} m_F c^2 + E^* &= \sqrt{(m_1 c^2)^2 + (p_1 c)^2} + \sqrt{(m_2 c^2)^2 + (p_2 c)^2} \\ &\approx m_1 c^2 + \frac{p_1^2}{2m_1} + m_2 c^2 + \frac{p_2^2}{2m_2}, \end{aligned} \quad (5)$$

lead to

$$\begin{aligned} (qc)^2 &= \frac{(m_F c^2 + E^*)^2}{4} + \frac{(m_1^2 c^4 - m_2^2 c^4)^2}{4(m_F c^2 + E^*)^2} - \frac{m_1^2 c^4 + m_2^2 c^4}{2} \\ &\approx \frac{2m_1 c^2 m_2 c^2 (m_F c^2 + E^*)}{m_1 c^2 + m_2 c^2} - 2m_1 c^2 m_2 c^2, \end{aligned} \quad (6)$$

where q is the relative momentum of the two particles, and E^* is the excitation energy of the decaying fragment. In the rest frame of the decaying fragment, the velocities of the two emitted particles become

$$\mathbf{v}_1^{(F)} = -\mathbf{q}/m_1, \quad (7)$$

$$\mathbf{v}_2^{(F)} = \mathbf{q}/m_2, \quad (8)$$

and the velocity of the lighter particle will always be greater than the velocity of the heavier particle.

If the velocity of the fragment in the laboratory system is $\mathbf{v}_F^{(L)}$, then the particle velocities in the laboratory system become

$$\mathbf{v}_1^{(L)} = \mathbf{v}_F^{(L)} + \mathbf{v}_1^{(F)} = \mathbf{v}_F^{(L)} - \mathbf{q}/m_1, \quad (9)$$

$$\mathbf{v}_2^{(L)} = \mathbf{v}_F^{(L)} + \mathbf{v}_2^{(F)} = \mathbf{v}_F^{(L)} + \mathbf{q}/m_2. \quad (10)$$

In applications of velocity-gated correlation functions, the particle velocities are calculated in some source system (intermediate velocity, target, or projectile residue source) with assumed velocity $\mathbf{v}_S^{(L)}$. The particle velocities in the source system become

$$\mathbf{v}_1^{(S)} = \mathbf{v}_1^{(L)} - \mathbf{v}_S^{(L)} = \mathbf{v}_F^{(L)} - \mathbf{q}/m_1 - \mathbf{v}_S^{(L)}, \quad (11)$$

$$\mathbf{v}_2^{(S)} = \mathbf{v}_2^{(L)} - \mathbf{v}_S^{(L)} = \mathbf{v}_F^{(L)} + \mathbf{q}/m_2 - \mathbf{v}_S^{(L)}. \quad (12)$$

The condition of the velocity gates, $v_1 > v_2$ ($v_1 < v_2$), can also be written as $v_1^2 - v_2^2 > 0$ ($v_1^2 - v_2^2 < 0$). Using the

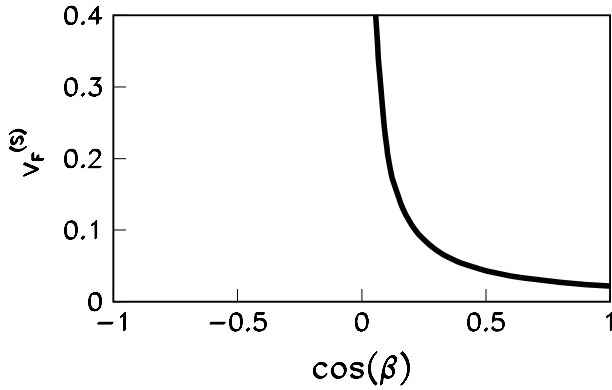


FIG. 2. Velocity condition in Eq. (14) for the decay ${}^5\text{Li} \rightarrow p + \alpha$. In the region above the thick line at the upper right corner, the condition $v_p^2 - v_\alpha^2 < 0$ holds.

particle velocities in the source system, we get

$$(v_1^{(S)})^2 - (v_2^{(S)})^2 = \frac{q}{\mu} \left[\frac{m_2 - m_1}{m_1 m_2} q - 2\mathbf{e}_q \cdot \mathbf{v}_F^{(S)} \right], \quad (13)$$

where \mathbf{e}_q is a unit vector directed along q , and $\mathbf{v}_F^{(S)} = \mathbf{v}_F^{(L)} - \mathbf{v}_S^{(L)}$ is the fragment velocity in the source frame. In a given decay, q , m_1 , and m_2 are determined by energy and momentum conservation, while the direction of \mathbf{q} can be considered to be isotropic. If we denote the angle between \mathbf{q} and $\mathbf{v}_F^{(S)}$ by β , the condition in Eq. (13) can be written

$$(v_1^{(S)})^2 - (v_2^{(S)})^2 = \frac{q}{\mu} \left[\frac{m_2 - m_1}{m_1 m_2} q - 2v_F^{(S)} \cos(\beta) \right]. \quad (14)$$

C. Results

From Eq. (14) it is clear that in the source system, the light particle does not always have a higher velocity than the heavier. The condition depends on the source velocity and on the angle between the relative momentum and the source velocity.

In Fig. 2, we present the regions where either the lighter or the heavier particle has the highest velocity. When the fragment velocity (in the source system) is small, the velocity condition in the fragment frame still holds (i.e., the light particle has the higher velocity). But, as the difference between the fragment velocity and the source velocity becomes larger, a larger fraction of events will have the velocity condition interchanged. However, it is important to note that the number of events for which the original velocity condition holds is always more than 50% assuming that \mathbf{q} is isotropically distributed. This means that if all particle pairs would come from two-body fragment decays, then the correlations in the gate where the lighter particle has the higher velocity (in whatever frame) will always be stronger than in the complementary gate. Thus, if the contrary behavior is observed, the dominating origin of particles must be other than two-body decay.

From Eq. (14) it is clear that the regions in the source system (as in Fig. 2) where either the lighter or the heavier particle has the highest velocity, depends on the relative momentum q in the decay. For a two-body decay that yields large values

of q , the region where the lighter particle has the highest velocity will be larger than that for decays yielding smaller values of q . This dependence is the main reason for the different results seen in Secs. IV C1 and IV C2 below.

In experimental data, the situation is somewhat more complicated because of limited angular coverage. The angular coverage may select certain regions in the $\cos(\beta)$ - $v_F^{(S)}$ plane that could change the above conclusions. It is not possible to find a simple expression for the velocity condition that includes the angular coverage of a given experiment. Instead, this has to be investigated numerically for each setup whenever velocity gates are used. In the next two sections, we present the results for two such investigations and show how they could be implemented.

1. Application to emission from projectile residue

In Ref. [19], velocity-gated small-angle two-particle correlation functions were used for protons, deuterons, tritons, and α particles, from the $E/A = 44$ and 77 MeV ${}^{40}\text{Ar} + {}^{27}\text{Al}$ collisions, at very forward angles, with the aim of studying emission from the projectile-like residue (PLS). Figure 3 shows velocity-gated p - α -correlation functions for the $E/A = 44$ MeV reaction. One can note that in the region $q \sim 54$ MeV/c, corresponding to the two-body decay of ${}^5\text{Li}$, the gate $v_\alpha > v_p$ shows larger correlations than the complementary gate $v_\alpha < v_p$. One possible deduction from this observation (and from the discussion in the previous section) would be that these particles must have a different origin than decay from ${}^5\text{Li}$. However, before such a conclusion can be drawn, we must rule out that the very specific angular coverage of $0.7^\circ < \theta < 7^\circ$ in Ref. [19] does not impose such constraints in the $\cos(\beta)$ - $v_F^{(S)}$ plane of Fig. 2, that the velocity condition is interchanged.

To investigate this issue, we performed simple numerical simulations, in which we assumed that the proton and α particle

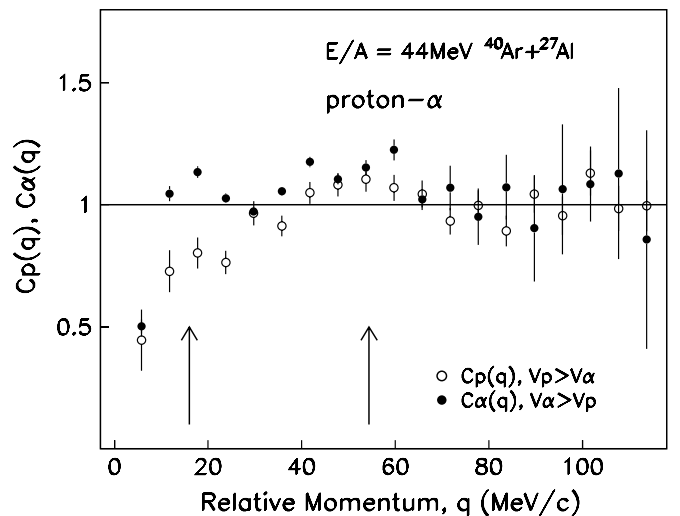


FIG. 3. Experimental velocity-gated $p\alpha$ -correlation function of Ref. [19]. Arrows indicate positions of different fragment decays (see Ref. [19]).

TABLE I. Fraction of $p\alpha$ pairs emitted in the two-body decay of ${}^5\text{Li}$ which have $v_p^{(\text{PLS})} > v_\alpha^{(\text{PLS})}$. Last column gives the fraction of “detected” pairs.

Fragment source	All pairs $v_p^{(\text{PLS})} > v_\alpha^{(\text{PLS})}$	$0.7 < \theta_{\text{lab}} < 7.0^\circ$ $E_k/A > 35 \text{ MeV}$	
		Detected	$v_p^{(\text{PLS})} > v_\alpha^{(\text{PLS})}$
TLS	54.3%	0.00%	
IS	58.6%	0.03%	84.7%
PLS	76.9%	2.27%	82.8%

come from the decay of ${}^5\text{Li}$, and that ${}^5\text{Li}$ has been emitted from different sources. We require that the proton and α particle come within the angular range of the detectors ($0.7^\circ < \theta < 7^\circ$) and be above the energy threshold of $35A \text{ MeV}$, imposed in Ref. [19]. The results are summarized in Table I.

The first row shows the results of when we assume that ${}^5\text{Li}$ has been emitted from a target-like residue source (TLS) of temperature 7 MeV . We deduce the kinetic energy of ${}^5\text{Li}$ from a Boltzmann distribution, assume that the emission is isotropic in the TLS frame, and boost ${}^5\text{Li}$ with the TLS velocity in the laboratory frame. The TLS velocity is taken normally distributed around the mean value of $0.02c$ with a standard deviation of $0.01c$. The decay of ${}^5\text{Li}$ is assumed to be isotropic, while the magnitude of the proton and α velocities in the ${}^5\text{Li}$ frame is determined from the energy and momentum conservation in the decay. Finally, the proton and α velocities are calculated in the frame of the projectile-like residue source (PLS), which is assumed to have the velocity $0.27c$ along the beam direction. We used 200 000 events in the simulations. The second column in Table I shows the percentage of *all* events, irrespective of detection, in which the proton had a higher velocity in the PLS frame than the α particle. The third column shows the percentage of events in which both particles fell within the angular range of the detectors and above the imposed energy threshold. The fourth column shows the percentage of the events in column three in which the proton had a higher velocity in the PLS frame than the α particle. For the intermediate velocity source (IS) and the PLS, we assumed temperatures of 20 and 7 MeV , respectively, and source velocities normally distributed around the mean values $0.15c$ and $0.27c$, respectively, with standard deviations of 0.02 and 0.01 .

As seen in Table I, the experimental filter in this case strengthens the velocity condition in the ${}^5\text{Li}$ frame, as compared to the unfiltered result (column 2). This means that if the protons and α particles in the region $q \sim 54 \text{ MeV}/c$, would come entirely from the decay of ${}^5\text{Li}$, more than 80% of the pairs would come in the gate $v_p^{(\text{PLS})} > v_\alpha^{(\text{PLS})}$ and this correlation function would be much higher than the complementary gate. Since this behavior is not observed, it should be safe to conclude that the protons and α particles contributing to the correlations in Fig. 3 (in the region $q \sim 54 \text{ MeV}/c$) must have another origin than decay of ${}^5\text{Li}$. In Ref. [19], it is assumed that these particles are emitted independently from the PLS source, and that the correlations originate from final state interaction between particles emitted close in space and time.

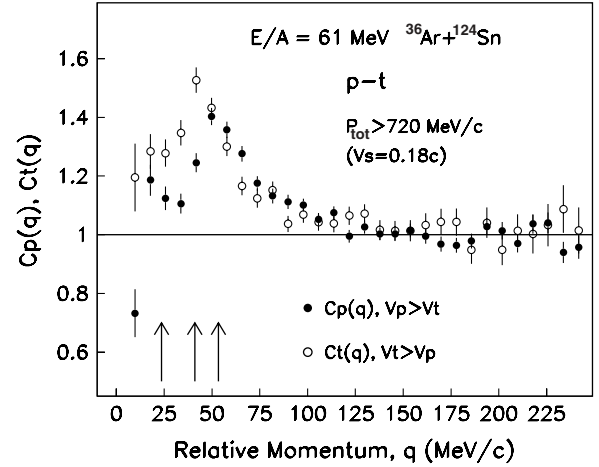


FIG. 4. Experimental velocity-gated pt correlation of Ref. [20]. Arrows indicate the positions of different fragment decays (see Ref. [20]).

2. Application to intermediate velocity source emission

In this section, we present numerical simulations similar to those presented in Sec. IV C1, but for a different reaction and experimental filter. In Ref. [20], velocity-gated small-angle two-particle correlation functions were used to deduce the emission chronology of protons, deuterons, and tritons from the $E/A = 61 \text{ MeV } {}^{36}\text{Ar} + {}^{112,124}\text{Sn}$ collisions. Figure 4 illustrates velocity-gated pt -correlation functions for the ${}^{36}\text{Ar} + {}^{124}\text{Sn}$ reaction. In this case, the angular coverage is $30^\circ < \theta < 114^\circ$, and the source of particle emission is assumed to be the intermediate velocity source (IS). In particular, we used the parameters summarized in Table II.

The results of the simulations are presented in Table III. We see that also in this case the velocity condition from the ${}^4\text{He}$ frame holds, even though for a substantial part of the pairs ($\sim 43\%$) the triton has a higher velocity than the proton in the IS frame.

This means that if the protons and tritons in the region $q \sim 24 \text{ MeV}/c$ would come entirely from the decay of ${}^4\text{He}$, then more than 56% of the pairs would come in the gate $v_p^{(\text{IS})} > v_t^{(\text{IS})}$, and this correlation function would be higher than the complementary gate. Since this is not observed, it should also in this case be safe to conclude that the protons and tritons contributing to the correlations of Fig. 4 (in the region $q \sim 24 \text{ MeV}/c$) must have a different origin than ${}^4\text{He}$ decay. In Ref. [20], it is assumed that these particles are emitted independently from the IS source, and that the correlations originate from final state interaction between particles emitted close in space and time.

TABLE II. Parameters used in the simulation in Sec. IV C2.

Fragment source	T (MeV)	$\langle v \rangle / c$	σ_v / c
TLS	7	0.01	0.01
IS	20	0.18	0.02
PLS	7	0.31	0.01

TABLE III. The fraction of pt pairs emitted in the two-body decay of ${}^4\text{He}$ which have $v_p^{(\text{PLS})} > v_t^{(\text{PLS})}$. Last column gives the fraction of “detected” pairs.

Fragment source	All pairs $v_p^{(\text{PLS})} > v_t^{(\text{PLS})}$	$30 < \theta_{\text{lab}} < 114^\circ$ $E_k > 10 \text{ MeV}$	
		Detected	$v_p^{(\text{PLS})} > v_t^{(\text{PLS})}$
TLS	52.5%	0.16%	56.4%
IS	56.5%	14.97%	56.9%
PLS	53.2%	0.52%	58.9%

V. SUMMARY

Two-particle intensity interferometry is an important tool for accessing information on the space-time characteristics of particle-emitting sources at intermediate-energy heavy ion collisions. In particular, when pairs of nonidentical particles are detected in coincidence, particle-velocity-gated correlation functions can be used to establish the emission time sequence, in a model-independent way. Since the particle velocities have to be calculated in the frame of the emitting source, the main

uncertainty in the method comes from the uncertainty in the source velocity, mostly originating from impact parameter averaging implicitly performed in experiments. We have demonstrated how the error due to uncertainties in the source velocity can be estimated by numerical simulations. An example presented of such an investigation makes it plausible that for most cases, the error will be small, only a few percent.

A more serious problem may be posed by the fact that for the particle-velocity-gated correlation function method to work, the particles have to be emitted independently by the source. Clearly, this is not always the case, as particle pairs may originate from the two-body decay of excited fragments. We have demonstrated that the kinematical signature of two-body decay is strong in the particle-velocity-gated correlation functions. This leads to an expected behavior, namely, that the correlations in the gate where the lighter particle has the higher velocity are stronger than in the complementary gate. This ensures that when the contrary behavior is observed, the dominating origin of particles must be other than two-body decay. As examples, two experimental cases demonstrate that it is possible to deduce the emission chronology, even if there is a contribution from two-body decay.

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- [1] S. E. Koonin, Phys. Lett. **B70**, 43 (1977).
[2] D. H. Boal, C. K. Gelbke, and B. K. Jennings, Rev. Mod. Phys. **62**, 553 (1990).
[3] D. Ardouin, Int. J. Mod. Phys. E **6**, 391 (1997).
[4] U. Heinz and B. V. Jacak, Annu. Rev. Nucl. Part. Sci. **49**, 529 (1999).
[5] Y. Laroche et al., Phys. Rev. C **55**, 1869 (1997).
[6] J. Lukasik et al., Phys. Rev. C **55**, 1906 (1997).
[7] D. Dorò et al., Phys. Lett. **B491**, 15 (2000).
[8] T. Lefort et al., Nucl. Phys. **A662**, 397 (2000).
[9] G. Lanzaò et al., Nucl. Phys. **A683**, 566 (2001).
[10] W. G. Gong et al., Phys. Lett. **B246**, 21 (1990).
[11] G. Verde, D. A. Brown, P. Danielewicz, C. K. Gelbke, W. G. Lynch, and M. B. Tsang, Phys. Rev. C **65**, 054609 (2002).
[12] D. O. Handzy et al., Phys. Rev. Lett. **75**, 2916 (1995).
[13] Ph. Eudes, Z. Basrak, and F. Sebille, Phys. Rev. C **56**, 2003 (1997).
[14] S. Pratt and M. B. Tsang, Phys. Rev. C **36**, 2390 (1987).
[15] R. Lednicky, V. L. Lyuboshitz, B. Erasmus, and D. Nouais, Phys. Lett. **B373**, 30 (1996).
[16] R. Ghetti et al., Phys. Rev. Lett. **87**, 102701 (2001).
[17] R. Ghetti et al., Phys. Rev. Lett. **91**, 092701 (2003).
[18] R. Ghetti, J. Helgesson, V. Avdeichikov, B. Jakobsson, N. Colonna, and H. W. Wilschut, Phys. Rev. C **70**, 034601 (2004).
[19] R. Ghetti et al., Nucl. Phys. **A765**, 307 (2006).
[20] R. Ghetti et al., nucl-ex/0507029.
[21] G. Verde, P. Danielewicz, D. A. Brown, W. G. Lynch, C. K. Gelbke, and M. B. Tsang, Phys. Rev. C **67**, 034606 (2003).
[22] D. A. Brown and P. Danielewicz, Phys. Rev. C **64**, 014902 (2001).
[23] D. A. Brown and P. Danielewicz, Phys. Lett. **B398**, 252 (1997).
[24] D. A. Brown and P. Danielewicz, Phys. Rev. C **57**, 2474 (1998).
[25] R. Ghetti et al., Nucl. Phys. **A674**, 277 (2000).
[26] C. J. Gelderloos and J. M. Alexander, Nucl. Instrum. Methods A **349**, 618 (1994).
[27] C. J. Gelderloos et al., Phys. Rev. Lett. **75**, 3082 (1995).
[28] S. J. Gelderloos et al., Phys. Rev. C **52**, R2834 (1995).
[29] S. Voloshin, R. Lednicky, S. Panitkin, and N. Xu, Phys. Rev. Lett. **79**, 4766 (1997).
[30] D. Ardouin et al., Phys. Lett. **B446**, 191 (1999).
[31] J. Pochodzalla et al., Phys. Rev. C **35**, 1695 (1987).
[32] P. A. DeYoung, M. S. Gordon, X. Lu, R. L. McGrath, J. M. Alexander, D. M. deCastro Rizzo, and L. C. Vaz, Phys. Rev. C **39**, 128 (1989) and references therein.
[33] P. A. DeYoung et al., Phys. Rev. C **41**, R1885 (1990) and references therein.