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Proton evaporation time scales from longitudinal and transverse two-proton correlation functions

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Two-proton correlation functions for the inverse kinematics reaction ^{129}Xe+^{27}Al at $E/A = 31$ MeV have been reanalyzed to search for differences between longitudinal and transverse correlations indicative of emission from a long-lived composite system. Evidence for such differences is found when tight angular cuts are applied in the compound nucleus rest frame and when the correlation functions are constructed by the event-mixing technique.

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Two-proton correlation functions probe the space-time structure of the proton-emitting source through the spatial dependence of final-state interactions (due to the nuclear force and Coulomb repulsion between the protons) and quantum interference effects [1–33]. For protons of a given velocity **v**, the strength of the final-state interaction mainly depends on the magnitude of the spatial separation between emitted protons, while directional information is carried by the quantum mechanical antisymmetrization which leads to a suppression of the correlation function at small relative momenta **q**. Emission from long-lived sources produces elongated phase space distributions [3–5] which should lead to detectable differences between longitudinal and transverse correlation functions with **q** oriented parallel and perpendicular to **v**, respectively.

Past experimental searches for this predicted lifetime effect [7–12] have either led to negative or statistically insignificant results, and it was suggested [12] that insufficient characterization of the source velocity may obscure the effect. Indeed, the only clear observation [6] of significant differences between longitudinal and transverse correlation functions was reported for the emission of low-energy protons in central ^{36}Ar+^{45}Sc collisions, in an experiment which utilized a 4π detector for full event characterization. Emission from a well-defined source and application of the longitudinal and transverse cuts in the rest frame of that source were pointed out to be essential for observing the predicted lifetime effect [6].

In a previous analysis of inclusive two-proton correlation functions [9,10], longitudinal and transverse correlation functions were defined in terms of the angle $\psi_{\text{lab}} = \cos^{-1}(\mathbf{q}\cdot\mathbf{P}/qP)$ between the relative momentum **q** and the total momentum **P** of the coincident proton pair as viewed in the laboratory rest frame. As discussed in Ref. [6], such an analysis may fail to observe the predicted lifetime effect. In light of this consideration, we have reanalyzed the high-statistics proton coincidence data [9,10] for the inverse kinematics reaction ^{129}Xe+^{27}Al at $E/A = 31$ MeV. For the reaction, ambiguities of the emitting source velocities are relatively small, ranging from $\beta = 0.209$ for complete fusion reactions to $\beta = 0.251$ for emission from excited projectile fragments [10], and lifetime effects should be observable without further event characterization. (Emission from a target-like source was suppressed by a cut on the total laboratory momenta of the coincident proton pairs, $P_{\text{lab}} \geq 480$ MeV, selecting average proton velocities of $\beta_{\text{lab}} \approx P_{\text{lab}}/2m_p > 0.25$.) Indeed, we observe a difference between longitudinal and transverse correlation functions consistent with emission from a long-lived source when tight angular cuts are made in the compound nucleus rest frame and when the correlation functions are constructed via the mixed-event technique.

Details of the experiment were given in Refs. [9,10]. For clarity, we repeat essential information on the detection system; it was comprised of two arrays of ΔE-E telescopes consisting of 300–400 μm thick silicon detectors backed by 10 cm long CsI(Tl) or NaI(Tl) detectors. An array of 37 Si-CsI(Tl) telescopes was centered at polar and azimuthal lab angles of $\theta = 25°$ and $\phi = 0°$. Each telescope covered a solid angle of $\Delta\Omega = 0.37$ msr with

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a nearest-neighbor spacing of $\Delta\theta = 2.6°$. Centered at $\theta = 25°$ and $\phi = 90°$ was an array of 13 Si-NaI(Tl) telescopes, each covering $\Delta\Omega = 0.5$ msr of solid angle with a nearest-neighbor spacing of $\Delta\theta = 4.4°$. The energy resolution was on the order of 1%.

The experimental two-proton correlation function is defined according to

$$1 + R(\mathbf{q}) = C\frac{N_{\mathrm{coinc}}(\mathbf{q})}{N_{\mathrm{back}}(\mathbf{q})}, \tag{1}$$

where $N_{\mathrm{coinc}}(\mathbf{q})$ represents the yield of coincident proton pairs with relative momentum $\mathbf{q}$. Different from the analysis of Refs. [9,10], we chose to construct the background yield, $N_{\mathrm{back}}(\mathbf{q})$, by means of the event-mixing technique [34,35]. The mixed-event technique is preferable in view of small differences in the shapes of the single- and two-proton inclusive energy spectra, most likely due to different relative contributions to the single- and two-particle inclusive spectra from decays of projectile and fusion residues. Indeed, use of the singles technique, employed by Ref. [10], caused slight distortions in the shape of the correlation functions which partially masked the lifetime effect. The normalization constant C is adjusted such that $R(q)$ vanishes for large q; it was determined independently of the angle $\psi = \cos^{-1}(|\mathbf{P}\cdot\mathbf{q}/|\mathbf{P}|\cdot|\mathbf{q}|)$.

Proton emission from a long-lived source leads to a phase space distribution elongated in the direction of the total momentum [3–6] as viewed in the rest frame of the emitting source. For such distributions, the Pauli suppression of the correlation function at low q is strongest for those proton pairs whose relative momentum lies perpendicular to the direction of elongation. Pauli suppression is weak along directions of $\mathbf{q}$ with significant components along the direction of elongation. Different from Refs. [9,10], we employed a narrower gate in the transverse direction ($\psi = 80°$–$90°$ as compared to $\psi = 60°$–$90°$) to preserve, as much as possible, the effect of maximal Pauli suppression. The longitudinal cut is less critical and can be made wide. Our choice of $\psi = 0°$–$50°$ (compared to $\psi = 0°$–$40°$ used in Refs. [9,10]) was largely motivated by the need for adequate statistics.

Cuts on ψ, defined in the rest frame of the source, are optimized to reveal finite lifetime effects in the correlation function [6]. The relative orientation of $\mathbf{P}$ and $\mathbf{q}$ is a function of the rest frame (since $\mathbf{P}$ depends on the rest frame, but $\mathbf{q}$—at least in the nonrelativistic limit—does not). Definition of ψ in a reference frame which moves rapidly with respect to the rest frame of the source may, therefore, attenuate the difference between longitudinal and transverse correlation functions [6,12].

The improvements in analysis are illustrated in Fig. 1. The three panels show longitudinal (filled symbols) and transverse (open symbols) two-proton correlation functions selected by the cut on the total laboratory momentum $P \geq 480$ MeV/c. In the top panel, the angle $\psi = \psi_{\mathrm{c.m.}}$ was defined in the center-of-momentum frame of projectile and target, i.e., in the rest frame of the compound nucleus ($\beta = 0.209$). As discussed above, the rest frame is close to that of the emitting source. In the center panel, ψ_{lab} was defined in the laboratory system ($\beta = 0$). Consistent with the results of Refs. [9,10], no significant differences between longitudinal and transverse correlation functions are observed when ψ is defined in the laboratory rest frame. When the angle ψ is defined in the rest frame of the compound nucleus, however, significant differences between longitudinal and transverse correlation functions emerge indicating that the applied cuts are better aligned with the long and short axes of the spatial distribution of emitted particles (moving with fixed velocity towards the detector). The bottom panel illustrates the loss in resolution when the transverse cut is widened to $\psi_{\mathrm{c.m.}} = 60°$–$90°$.

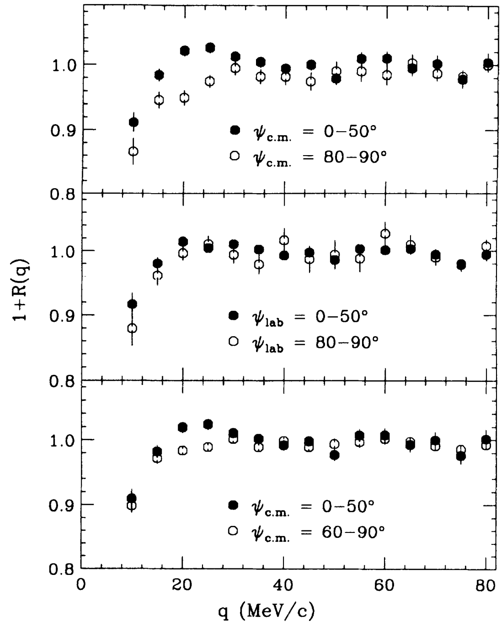

FIG. 1. Longitudinal (filled circles) and transverse (open circles) two-proton correlation functions for the reaction ^{129}Xe+^{27}Al at $E/A = 31$ MeV. Angular cuts in the top and bottom panels were constructed in a rest frame moving in the lab with $\beta = 0.2086$. Angular cuts in the center panel were constructed in the laboratory frame. The cut on the total momentum of the proton pair was $P \geq 480$ MeV/c. The widths of the applied cuts in ψ are indicated in the figure.

The Koonin-Pratt formalism [1–3,5] allows the construction of the two-proton correlation function from the single-particle emission function $g(\mathbf{r}, t, \mathbf{p})$, which is a function of the space-time emission coordinates $\mathbf{r}$ and t, as well as the momentum $\mathbf{p}$ [3,5,10] of the emitted particles. To illustrate the sensitivity of the correlation function to the average spatial dimension and lifetime of the emitting system, we use a parametrized source function, simulating emission from the surface of a sphere of radius R and assuming an exponential lifetime τ [36]. Energy and angular distributions of the emitted protons were obtained by sampling the experimental yield $Y(\mathbf{p})$. In the rest frame of the source, the source function was described as

$$g(\mathbf{r}, t, \mathbf{p}) \sim \delta(|\mathbf{r}| - R)\theta(\mathbf{r}\cdot\mathbf{p})\frac{\mathbf{r}\cdot\mathbf{p}}{|\mathbf{r}|\cdot|\mathbf{p}|}Y(\mathbf{p})\exp(-t/\tau), \tag{2}$$

where $\theta(x)$ is the unit step function which vanishes for $x < 0$, and $\delta(x)$ is the delta function which vanishes

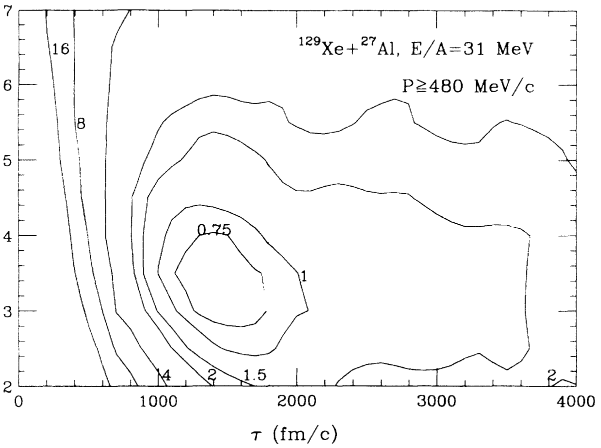

FIG. 2. Contour plots of χ^2/ν (chi-squared per degree of freedom) evaluated by comparing measured longitudinal and transverse correlation functions (over the range of 15 MeV/$c \leq q \leq$ 40 MeV/c) to those predicted for emission from a schematic source [Eq. (2)] with radius and lifetime parameters R and τ.

for $x \neq 0$. The source was assumed to be at rest in the center-of-momentum system, and the emitted particles were then boosted into the laboratory rest frame (β = 0.2086). Longitudinal and transverse correlation functions for a given R and τ were calculated according to the Koonin-Pratt formalism [5].

For a given parameter set R and τ, the agreement between measured and calculated correlation functions was quantified by the value of χ^2/ν (chi-squared per degree of freedom) evaluated in the region q = 15–40 MeV/c. Contour plots of χ^2/ν as a function of the parameters R and τ are shown in Fig. 2. The best agreement between measured and calculated correlation functions is obtained for source radii of $R \approx$ 3–4 fm and extracted emission times of $\tau \approx 1400 \pm 300$ fm/c.

Longitudinal and transverse correlation functions calculated for R = 3.5 fm and τ = 1300 fm/c are shown as solid and dashed curves in Fig. 3. As in the top panel of Fig. 1, the cuts on ψ were applied in the center-of-mass system. The calculations reproduce the observed difference between longitudinal and transverse correlations functions rather satisfactorily.

The extracted source radius is smaller than that of the compound nucleus. The reason for such a small source radius is not fully understood. It may reflect an artifact of the present schematic source parametrization which assumes emission according to Lambert's law and neglects anisotropies of emission resulting from angular momentum effects. Furthermore, for protons emitted close to the Coulomb barrier, distortions in the Coulomb field of the emitting residue may not be negligible, and the Koonin-Pratt formula may be deficient [37].

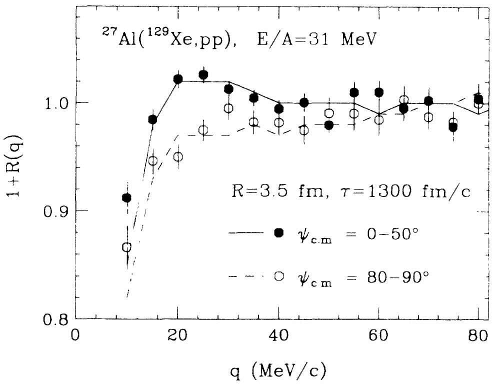

FIG. 3. Comparison of measured (points) and calculated (curves) correlation functions. The calculations were performed for emission from a schematic source [Eq. (2)] with radius and lifetime parameters R = 3.5 fm and τ = 1300 fm/c.

In conclusion, we have reanalyzed the ^{129}Xe+^{27}Al data of Refs. [9,10] and searched for differences between longitudinal and transverse two-proton correlation functions predicted for large emission time scales. When the relative angle ψ between **P** and **q** is constructed in the center-of-momentum frame of the projectile-target system, such differences are observed. The effect becomes washed out when the angle ψ is constructed in the laboratory frame (as was done in Refs. [9,10]). Use of the event-mixing technique proved advantageous, as was the use of tight cuts in the transverse direction. The present experiment does not provide unique source characterization since emissions from projectile and fusion residues could not be separated. Impact-parameter selected measurements, such as those of Ref. [6], allow much better event characterization and can thus provide much more stringent tests of theoretical predictions. The present results are sufficiently encouraging to warrant such improved experiments probing the time scales of compound nuclear decays.

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