Quantum-Statistical Interference of Coincident Neutrons from the Compound Nucleus

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(Received 22 January 1990)

Coincident neutrons from the $^{18}O+^{26}Mg \rightarrow ^{44}Ca$ ($E_x = 60$ and 71 MeV) compound-nuclear reaction show an anticorrelation at small relative momentum, giving evidence for quantum-statistical interference in analogy to the optical Hanbury-Brown and Twiss effect. An average decay width of 60 keV is extracted from the measured energy correlations. The deduced extension of the neutron wave packets exceeds by far the *nn* scattering length, in accordance with the observed insignificance of the attractive *nn* final-state interaction.

PACS numbers: 25.70.Gh, 24.60.Dr

Second-order interferences in the coincidence distributions of identical particles from a chaotic source are a consequence of quantum statistics.[1-3] At small relative momentum the probability for the occurrence of coincidences is enhanced or decreased, as compared to the product of the single-particle probabilities, by the symmetrization or antisymmetrization of the wave function for bosons or fermions, respectively. Bosonic correlations of this type have been observed with photons, e.g., from a distant star (Hanbury-Brown and Twiss effect[4]), and with mesons, e.g., pions from antiproton-proton[5] or heavy-ion[6,7] collisions.

For nucleons, and for fermions in general, a clear-cut observation of the analogous antisymmetrization effect is still lacking. Instead, measured nucleon-nucleon correlations are found to be dominated by the final-state strong and Coulomb interactions.[8-11] For example, in the case of neutron-neutron coincidences the only published experiment,[12] studying 7.5-GeV/c proton-nucleus collisions, shows an enhancement at small relative momentum, resulting from the attractive singlet S-wave interaction.

A dominance of final-state interactions for simultaneous emission is understood, within various theoretical approaches,[13-15] as being due to the excess of the nucleon-nucleon scattering lengths over the source radii. With increasing lifetime of the source, however, the increasing average separation of successive nucleons will reduce the significance of final-state strong interactions.[13-15] This tendency is indicated by experimental proton-proton correlations,[11,16] which become Coulomb dominated at compound-nuclear lifetimes.[16,17] For neutrons it is suggested by these trends, and by detailed calculations,[15] that the purely quantum-statistical correlations should become visible for lifetimes that correspond to wave packets extended much farther than the singlet scattering length $a_{nn} \approx 16$ fm.

In the neutron-neutron correlation function,

$$C(\mathbf{p}_1,\mathbf{p}_2) = \mathrm{const} \times \sigma_{\mathrm{coinc}}(\mathbf{p}_1,\mathbf{p}_2)/\sigma_{\mathrm{single}}(\mathbf{p}_1)\sigma_{\mathrm{single}}(\mathbf{p}_2) , \quad (1)$$

the signature of quantum-statistical interference is a dip at momentum difference $\mathbf{p}_1 - \mathbf{p}_2 = 0$.[2,3] In analogy to the optical case, the transverse and the longitudinal widths of the dip reflect the source's radius and lifetime, respectively. The depth is independent of these parameters and amounts to $\frac{1}{2} C(\mathbf{p}_1 - \mathbf{p}_2 \rightarrow \infty)$ for random spin orientation. These features are opposed to those of the peaking at $\mathbf{p}_1 - \mathbf{p}_2 = 0$ that would arise from the attractive spin-singlet final-state interaction.

Here we report on experiments which show the signature of quantum-statistical interference in the correlations of coincident neutrons from the $^{18}O+^{26}Mg$ compound-nuclear reaction.[18] Final-state interactions are found to be insignificant, which is attributed to the large extension of the neutron wave packets and, of course, to the absence of the Coulomb interaction. Hence, these experiments establish the purely wave-mechanical second-order interference effect for nucleons, in close analogy to the original Hanbury-Brown–Twiss experiments for photons.

Isotopically enriched ^{26}Mg targets of 2- and 5-mg/cm^2 areal density were bombarded with pulsed ^{18}O beams of 65- and 88-MeV incident energy provided by the Munich MP tandem accelerator.[19] Neutrons were detected by means of four large NE213 scintillator counters of cylindrical form (diameter 8 cm, height 100 cm) with photomultipliers at both ends.[20] These counters were placed in pairs symmetrical to the beam axis (Fig. 1) at a distance of 2 m from the target, mounted in a small scattering chamber. The neutron energy was determined from the time of flight with an overall resolution varying between 200 and 1100 keV full width at half maximum (FWHM) for energies in the accepted range between 2 and 10 MeV, respectively. γ rays were discriminated by their different time of flight (which was also used for calibration) and, additionally, by their different scintillation pulse shapes.

Coincidences were recorded simultaneously for two pairs of detectors in close proximity at angles θ_1, θ_2 and $-\theta_1, -\theta_2$ and for two pairs of distant detectors at angles $\theta_1, -\theta_2$ and $-\theta_1, \theta_2$. This setup, with each detector tak-

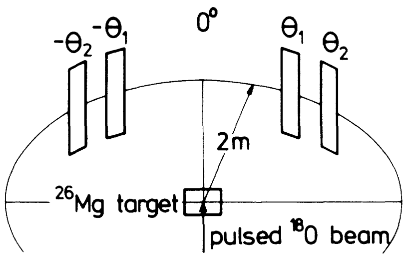

FIG. 1. Schematic view of the experimental setup with four time-of-flight neutron spectrometers.

ing part in a close and a far combination, offers the advantage of canceling detection efficiencies in the double ratio of coincidence yields,

$$\frac{N(\theta_1,\theta_2)N(-\theta_1,-\theta_2)}{N(\theta_1,-\theta_2)N(-\theta_1,\theta_2)} = \left[\frac{\sigma_{\rm lab}(\theta_1,\theta_2)}{\sigma_{\rm lab}(\theta_1,-\theta_2)}\right]^2 . \quad (2)$$

Double ratios consistent with unity, obtained for neutrons from different pulses of the beam, confirm proper operation. The results for true coincidences have been corrected for the contributions from accidental coincidences.

Cross talk due to the scattering of neutrons from one detector into the neighboring one, leading to unwanted coincidences, was suppressed by means of borated polyethylene shieldings. The shielding efficiency was measured with neutrons from a ^{241}Am/^{9}Be source in the target position. It was found that contributions from cross talk were negligible for small time-of-flight differences (< 14 ns) due to the spacing of the detectors, and for the complete range when a threshold corresponding to a minimum energy of 3 MeV was set on the scintillator pulse height.

Neutron singles spectra, recorded simultaneously, show Maxwellian-like shapes in agreement with the expectation for compound-nuclear decay succeeding the ^{18}O+^{26}Mg fusion reaction. The mean energy of the detected neutrons is 5.2 MeV, corresponding to 3.1 MeV in the c.m. system. From the systematics of fusion cross sections,[21] fusion is estimated to cover 80% of the total reaction cross section. Projectile breakup can be excluded as a relevant source of the coincidence yields by its different kinematics.

The coincidence data are represented in Fig. 2 in the form of double ratios [Eq. (2)] as a function of the difference Δt of the times of flight recorded on-line. In the two separate experiments at $E_l = 88$ MeV [Figs. 1(a) and 1(b)] and 65 MeV [Fig. 1(c)][19] different angles were chosen, corresponding to 36°, 54° [(a),(b)], and 54°,72° [(c)] on the average in the c.m. system, with the same angular distance of coincident neutrons in the close geometries, $\langle\Delta\theta_{\rm c.m.}^{\rm close}\rangle = 20°$ (averaged over the detector extensions), and with $\langle\Delta\theta_{\rm c.m.}^{\rm far}\rangle \gtrsim 100°$ in the far geometries. These angular distances are substantially smaller

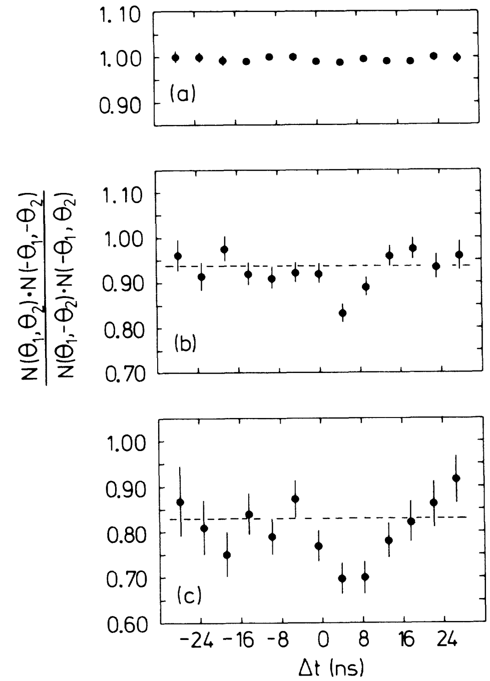

FIG. 2. Double ratio of coincidence yields, equivalent to $[\sigma_{\rm lab}(\Delta\theta^{\rm close})/\sigma_{\rm lab}(\Delta\theta^{\rm far})]^2$, as a function of the time-of-flight difference $\Delta t = t(\theta_2) - t(\theta_1)$ for 2-10-MeV neutrons from ^{18}O+^{26}Mg at $\theta_1,\theta_2 = 25°,38°$, $E_l = 88$ MeV [(a) for accidentals from successive pulses of the beam, and (b) for true coincidences] and at $\theta_1,\theta_2 = 38°,51°$, $E_l = 65$ MeV [(c) true coincidences]. The dashed lines represent the weighted averages of the double ratios in the ranges $\Delta t < -5$ ns and $\Delta t > 15$ ns. An energy difference $\Delta E_{\rm c.m.} = 0$ of neutrons from the compound nucleus corresponds in the laboratory system to $\Delta t = 4$–5 ns on the average.

and larger, respectively, than the expected[2] angular half-width of the interference effect, $\Delta\theta_{\rm c.m.} \approx \frac{1}{2}$ (neutron wavelength)/(nuclear diameter) = 55°. In accordance, constant true-to-accidental ratios of coincidence rates as a function of Δt were found in the far geometry.

While double ratios consistent with unity are obtained for uncorrelated neutrons from different events [Fig. 2(a)], distinctly lower levels are found for true coincidences [dashed lines in Figs. 2(b) and 2(c)] in accordance with a merely kinematic correlation. In the c.m. system after emission of the first neutron, the near and the far detectors appear with different solid angles. This recoil effect is found to depend only weakly on Δt and to be consistent with the observed levels.

Evidence for the quantum-statistical interference effect is provided by the dip between $\Delta t = 0$ and 10 ns observed with a significance of about 4 standard deviations in each of the two experiments. The position of the dip is consistent with an average $\Delta E_{\rm c.m.} = 0$, corresponding in the laboratory system to $\Delta t = 4$ ns (b) and 5 ns (c). No indication of an enhancement due to the attractive *nn* final-state interaction is found around these values at Δt.

To deduce the energy correlation, the times of flight were converted eventwise to neutron energies. The double ratio then yields, as a function of the energy difference $\Delta E_{\rm lab}$, the coincidence cross-section ratio of the close and far geometries and hence the correlation function, normalized to unity at large momentum difference,[8-11]

$$C_{\Delta\theta^{\rm close}} = (1/R)\sigma_{\rm lab}(\Delta\theta^{\rm close})/\sigma_{\rm lab}(\Delta\theta^{\rm far}) \,. \tag{3}$$

Using for the constant R the average of $\sigma_{\rm lab}(\Delta\theta^{\rm close})/\sigma_{\rm lab}(\Delta\theta^{\rm far})$ outside of a 3-MeV window around $\Delta E_{\rm c.m} = 0$, the recoil effect (see above) is approximately canceled. In accordance with the expectation of a dependence on only relative angles and energies, consistent correlation functions have been found in both experiments[22] with the same $\Delta\theta^{\rm close}$ and have therefore been averaged.

In the energy correlation (Fig. 3) the interference dip is observed again around that energy difference which corresponds to an average $\Delta E_{\rm c.m.} = 0$ ($\Delta E_{\rm lab} = -0.75$ MeV). The most important contributions to the width of about 1.5 MeV (FWHM) are the experimental resolution and the kinematic spreading for given $\Delta E_{\rm c.m}$ due to the summing over different evaporation steps.

For comparison, an *enhancement* from the final-state strong interaction[13-15] would have a half-width of $2\hbar/a_{nn} \approx 25$ MeV/c in both the longitudinal and the transverse momentum difference. For the present average neutron energy, the latter corresponds roughly to our $\Delta\theta^{\rm close}$ and the former to $\Delta E_{\rm lab} = 2.7$ MeV. This range of energy differences (FWHM $= 2\Delta E_{\rm lab}$) is much broader than the dip in Fig. 3, and a 5% fraction of the enhancement calculated for *simultaneous* emission[14] would have been detected.

For a quantitative analysis of the energy correlation we use the quantum-statistical expression[2,3]

$$C_{\Delta\theta^{\rm close}}(\Delta E) = 1 - \frac{C_{\Delta\theta^{\rm close}}(0)}{1 + (\Delta E/\Gamma)^2} \,, \tag{4}$$

where $\Gamma = \hbar/(\text{lifetime})$ denotes the decay width. While $C_{\Delta\theta^{\rm close}}(0) = 0.5$ holds for vanishing $\Delta\theta^{\rm close}$ and for random relative spin orientation, two minor corrections lead to a value of 0.55 in the present case: (i) The finite value of $\Delta\theta^{\rm close}$ results in a decrease by 10%, according to the predicted angular correlation,[2] and (ii) the polarization correlation of the neutrons, due to the preference for neutron spins to be parallel to the respective compound-nuclear spin, estimated according to Ref. 23, results in an increase by 20%. Additional correlations, which might arise from an alignment of the compound-nuclear spin along the direction of the first neutron, are considered as negligible since the angular momentum carried away by a neutron [$(1-2)\hbar$ on the average] is small compared to the compound-nuclear spin ($20\hbar$ on the average).

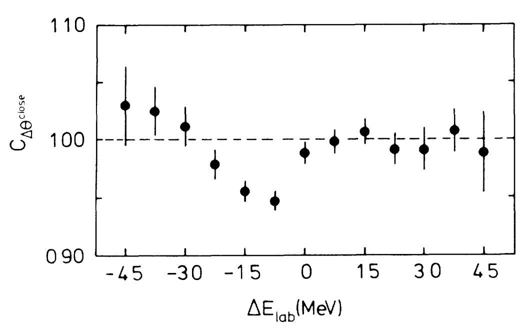

FIG. 3. Correlation function [Eq. (3)], averaged over both experiments, as a function of the energy difference $\Delta E_{\rm lab} = E_{\rm lab}(\theta_2) - E_{\rm lab}(\theta_1)$ for neutrons with $E_{\rm lab} = 3$–8 MeV.

To deduce an average decay width from the experimental correlation function, we use the content of the interference dip. Integration of the Lorentzian in Eq. (4) over ΔE yields $0.55\pi\Gamma$ for the area in the c.m. system. Its weighted average accounts for contributions from different evaporation steps. The experimental broadening reduces the depth of the dip but conserves, to a good approximation, its total area. Using the above expression, we obtain from the observed dip area (Fig. 3) the decay width

$$\langle\Gamma\rangle = 60 \pm 15 \text{ keV} \,,$$

which is the average over all nn decays in the evaporation chains of the primary highly excited ^{44}Ca nucleus.

According to statistical-model calculations,[24] the complete E_x range is approximately equally weighted by demanding that nn coincidences and about 50% of all neutron pairs are emitted in direct sequence at $E_x > 30$ MeV. The observed dip can be attributed almost entirely to this fraction, if the semiempirical systematics[25] of Γ roughly holds at $E_x < 30$ MeV, where it was established for medium-heavy nuclei,[25,26] and if the interference effect of neutrons separated by intermediate evaporation steps is not significant. With these assumptions, we derive from the experimental total average of Γ a more specific average for $E_x = 30$–71 MeV and $A = 39$–44 which amounts to $\Gamma = 110$ keV, corresponding to a lifetime $\tau = 6\times10^{-21}$ s.

Our experimental result enables a check of the quoted semiempirical dependence of Γ on the atomic number and on E_x, based on measurements of Ericson fluctuations (which are intimately related to the present effect[3,27]). The use of these for medium-heavy nuclei is limited to excitation energies below 30 MeV.[25,26] Extrapolation to the present case yields a range of Γ up to about 300 keV for the primary $\langle E_x\rangle \approx 65$ MeV, and weighting with the statistical-model nn branchings of the complete cascades, using the above assumption about nonconsecutive decays, yields $\langle\Gamma\rangle = 80$ keV. Since the low-E_x data follow the systematics only within a factor of 2,[25] the agreement is satisfactory.

A gross estimate of the extension of the neutron wave packets is given by the length $d = v_n\tau$. For a neutron velocity v_n corresponding to our average $E_{c.m}$ and for the compound-nuclear lifetime at $E_x = 30–71$ MeV, deduced above, we find $d = 150$ fm, which means that the mean separation of successive neutrons is much larger than the singlet scattering length a_{nn}. This is the condition, quoted at the outset, for the effects of the final-state interaction to become negligibly small.

Summarizing, intensity interferometry of the compound nucleus has been accomplished in a neutron-neutron coincidence experiment. The observed dip in the energy correlations is explained solely by the overlapping of the antisymmetrized wave packets and its size is consistent with the systematics of compound-nuclear decay widths.

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