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Evidence for lifetime effects on the two-particle correlation function at small relative momenta for ^{4}He induced reactions on ^{58}Ni at 120 MeV

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Small-angle correlations between two protons produced in the inclusive reaction $^4\mathrm{He}+{}^{58}\mathrm{Ni}\to p+p+X$ at 120 MeV have been measured. The data show an enhanced cross section for a relative energy $\Delta E \sim 400$ keV. Comparison with model calculations suggests an influence of a finite lifetime of the emitting source. A size parameter of 3 fm and a lifetime of $\sim 10^{-22}$ s were deduced.

In a search for localized heating (hot spots) in nucleus–nucleus collisions it was found [1] that proton spectra measured in coincidence with deep-inelastically scattered alpha-particles show up angle-dependent slope parameters. It was further found that the emission process is independent of the four-momentum transfer. Under the assumption of a fully equilibrated subsystem the number of nucleons sharing the excitation energy could be deduced. In order to prove these findings by a completely different method, we have measured small-angle correlations from approximately the same system as was previously investigated by Machner et al. [1].

The idea of deducing the size parameter of a statistically radiating source by the measurement of correlated bosons was first introduced and applied to astrophysics by Hanbury-Brown and Twiss [2], who measured photon–photon coincidences. Independently, Goldhaber et al. [3] applied it to microscopic physics by studying pion–pion correlations in proton–antiproton annihilations. They interpreted the dependence of the correlation function for small relative momenta between the two particles as due to quantum statistics. The two-particle correlation function, which is essentially the ratio between the coincident and the singles yields, shows besides quantum statistical effects other correlations like those from resonance decay or final state interactions. Such effects were taken into account by Koonin for two-proton correlation [4]. He suggested the inclusion of nuclear and Coulomb-induced final state interactions into the analysis. Whereas for bosons the correlation can vary between 1 and 2, it was shown by Koonin that for protons the correlation can become much larger due to final state interactions. For small relative momenta, $\Delta p \to 0$, the correlation $C = 1 + R$ vanishes because of the repulsive Coulomb force. Recent proton–proton correlation studies in heavy-ion-induced reactions are based on this approach [5,6]. However, in these studies possible lifetime effects were neglected, in contrast to the above cited pion measurements. It was recently realized that such a neglect may lead to a variation of the size parameter with ejectile energy and hence may lead to wrong conclusions on the underlying reaction mechanisms [7]. In the analysis of the present data we, therefore, have also studied the effect of a finite lifetime of the radiating source. A recent review on particle–particle correlations is given by Boal et al. [8].

We have measured two-particle correlations for the alpha-particle-induced reaction at $E = 120$ MeV on ^{58}Ni. The experiments have been performed with the KVI cyclotron. For the detection of protons a special detector was built. Detectors with a large solid angle for each proton and hence a large opening angle have a reduced efficiency in the low Δp region, since such

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proton pairs tend to go both into the same detector element. Previous experiments with relativistic heavy ion beams suffered from this effect [6] and no significant decrease in the correlation function for relative momenta below 20 MeV/c was observed. Therefore, the detector built for the present experiment consisted of three solid state counters with large areas. The first counter was a 292 μm thick silicon counter with seven strips on an area of 4 cm × 6 cm. This counter was followed by a high purity germanium counter with 6 mm thickness. On the front side of this counter was a pattern of five rectangular fields each of 32.0 mm × 7.95 mm. They were separated by small fields of 32.0 mm × 0.73 mm. Two adjacent fields were separated by a groove of 0.16 ± 0.01 mm width. The small fields acted as veto counters. The solid angle of each element is then defined by the larger fields. By this design a possible cross talk between neighboring elements could be avoided. The second counter was precisely mounted behind the inner five strips of the first counter in order to have five $\Delta E - E$ telescopes. A thick high purity germanium counter 13.5 ± 0.5 mm followed the telescopes and served as a veto counter. More details of the detector will be given elsewhere [9]. The counters were housed in a cryostat and the germanium counters were cooled with liquid nitrogen. This set-up was mounted in a scattering chamber with 120 cm diameter on a rotatable ring. The distance from the target to the surface of the element in the middle of the position sensitive germanium counter was 312.2 ± 1.0 mm. This leads to solid angles around 2.6 msr for each telescope. The angles between the centers of two telescopes was 1.7°. If the rectangular shape is taken into account an effective angle of 2.74° is obtained for neighboring and 6.97° for the telescopes farthest apart.

With this set-up we measured singles cross sections $d^3\sigma(p)/d^3p$ and coincident cross sections $d^6\sigma(p_1, p_2)/d^3p_1 d^3p_2$ for charged particles from protons to alpha-particles at a mean angle of 59.2°. At this large angle, contributions from projectile break-up are expected to be negligible. In this letter we restrict ourselves only to proton emission. The protons were measured with energies from 5 to 48 MeV. From the data the reduced two-particle correlation function $R(\boldsymbol{p}_1, \boldsymbol{p}_1)$ was deduced:

$$R(\boldsymbol{p}_1, \boldsymbol{p}_2) = \frac{\langle n \rangle^2 \sigma}{\langle n(n-1) \rangle} \frac{d^6\sigma_{1,2}}{d^3\sigma_1 d^3\sigma_2} - 1 , \qquad (1)$$

where σ is the total proton inclusive cross section and $\langle n \rangle$ is the particle multiplicity. Inclusive means in this context that we have no additional information on the remaining system X. In the present experiment we have fitted the first factor to the whole data sample in a region with large $\Delta\boldsymbol{p}$ where no correlation is expected to exist. In order to study the influence of different ejectile energies, a correlation function was extracted with a constraint on one of the proton energies being in the interval from 5 to 15 MeV or from 15 to 50 MeV (fig. 1). If the energy range is limited to compound nucleus evaporation (5–15 MeV) then only very small correlations are observed, i.e., $R(\Delta\boldsymbol{p}) \approx 0.3$. This result is in agreement with recent findings by De Young et al. [10]. These authors have studied two-proton correlations from the $^{16}O + ^{27}Al$ reaction at 140 MeV. At this energy the cross section is dominated by the compound nucleus mechanism. The data for the high energy interval in fig. 1 show a much stronger correlation than the low energy data. This enhancement around $\Delta p \approx 20$ MeV/c corresponding to a relative energy of $\Delta E = 400$ keV is due to the final state interaction of the two protons in the attractive singlet s-wave leading to a virtual $T = 1$ state in ^2He. The two functions were individually adjusted because of the different particle multiplicities for the different energy bins. The same observation, namely different correlations for different proton energies can be made from a different way of analyzing the data.

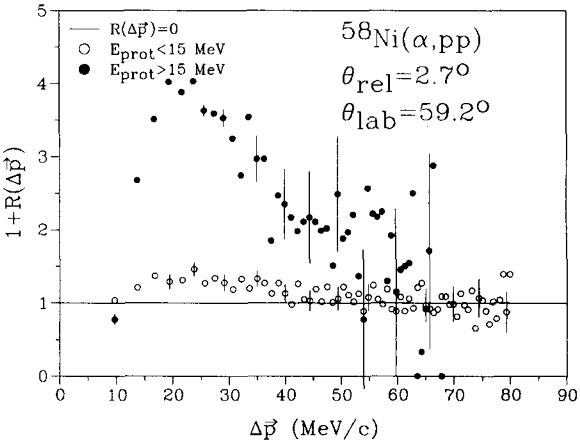

Fig. 1. Two-particle correlations for two protons with one having an energy from 5 to 15 MeV (open dots) or from 15 to 50 MeV (solid dots), respectively. Also shown are selected error bars.

In fig. 2 the inclusive correlation function $1+R$ without any constraint on the data is shown as a function of the sum of the two proton energies. The normalization factor was found to be $\langle n\rangle^2\sigma/\langle n(n-1)\rangle = 2220\pm 90$ mb. The data show an increasing correlation for increasing proton energies. The decrease above 80 MeV is a result of the limiting detector thickness. Also shown in this figure are calculations for the alpha-particle break-up performed in terms of the PWBA similar to the one in ref. [11] for the indicated angles. The wavefunctions are assumed to be of the Eckhart form [12]. The cross section is largest at small angles whereas at the angle of the present measurement the cross section is small and peaks at ≈ 17 MeV. This is an energy where almost no correlations are present. We can thus conclude that the present observed two-proton correlation does not have its origin in projectile fragmentation. The whole set of the data was then analyzed in terms of the Koonin model [4]. One should mention at this point that interactions between the emitted particles and the nucleus are neglected, which only at high energies seems a good approximation. Within this model the correlation function R for a source, which is gaussian distributed in space and time with dispersion parameters r_0 and τ, respectively, is given by

$$R(\boldsymbol{p}_1,\boldsymbol{p}_2) = \frac{1}{(2\pi)^{3/2} r_0^2 \rho} \int \mathrm{d}^3 r \exp\left(-\frac{r^2-(\boldsymbol{r}\cdot\boldsymbol{v}'\tau/\rho)^2}{2r_0^2}\right) \times \left[\tfrac{1}{4}|{}^1\Psi_{\Delta p}(\boldsymbol{r})|^2 + \tfrac{3}{4}|{}^3\Psi_{\Delta p}(\boldsymbol{r})|^2 - 1\right], \qquad (2)$$

where $\boldsymbol{r}$ is the relative distance, $\boldsymbol{v}'$ is a model velocity which is defined as the difference between the mean proton velocity $\boldsymbol{v}$ and the source velocity v_0. The latter is assumed to lie along the beam direction and is calculated below under the assumption that the source carries the full beam momentum. ${}^1\Psi$ is the two-proton wavefunction in the singlet state and ${}^3\Psi$ in the triplet state. These wavefunctions were calculated from the two-body Schrödinger equation including Coulomb- and nuclear potentials [13]. The effective size of the emission volume can be written as

$$\rho = \sqrt{r_0^2 + (v'\tau)^2}\,. \qquad (3)$$

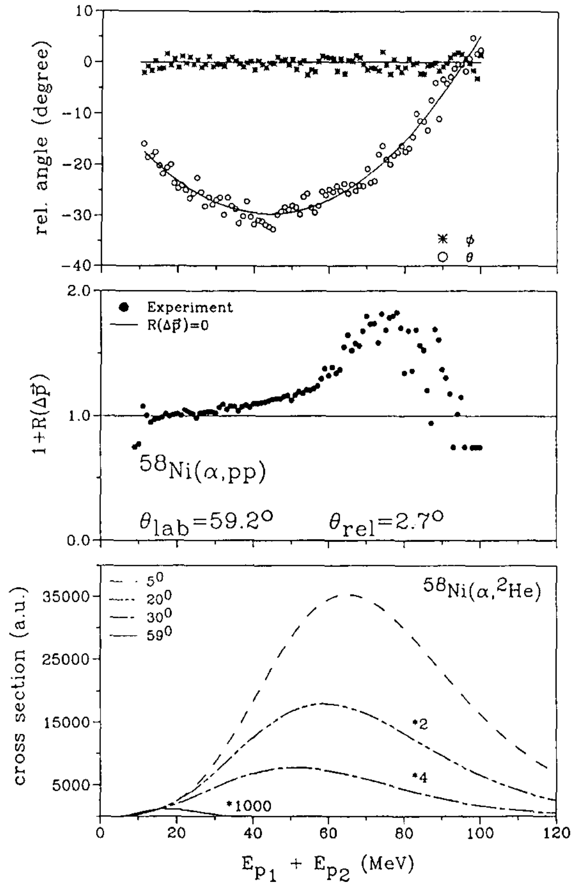

Fig. 2. The upper part of the figure shows Monte Carlo simulations for the angles between $\boldsymbol{v}'$ and $\Delta\boldsymbol{p}$ (see text). Also shown are a parabolic fit (solid curve) to the azimuth and a line corresponding to $\phi=0$. In the middle part the dependence of the experimental inclusive two-proton correlation function, i.e., with no further information on the residual system, on the sum of the two-proton energies is shown. In the lower part of the figure PWBA calculations for the alpha-particle break-up into two protons are shown as function of their total energy for the angles indicated. The cross sections are multiplied by the indicated factors.

In order to compare the present results with previous work [5,6,14,15] we first assume also $\tau=0$. The calculations for different spatial dispersions r_0 are shown together with the data as a function of the relative two-proton momenta Δp in fig. 3. The normalization is the same as in fig. 1. The data were best fitted with the choice $r_0=4$ fm. This is roughly the same value as found in ${}^{16}\mathrm{O}+{}^{197}\mathrm{Au}$ reactions at 25 MeV/nucleon and for symmetric heavy-ion collisions at 400 MeV [6]. For 1.8 GeV/nucleon a smaller value of 2.0 fm was reported [14].

However, we find it impossible to reproduce the

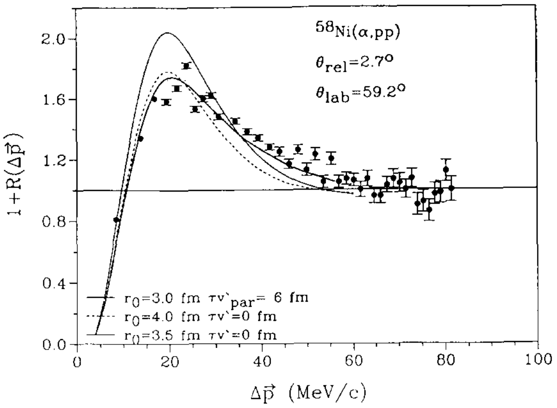

Fig. 3. Two-proton correlations. The experimental results are shown by dots with error bars. Model calculations are shown with $r_0 = 3.5$ fm and $\tau = 0$ as a thin solid curve, $r_0 = 4.0$ fm and $\tau = 0$ as a dashed curve, and $r_0 = 3.0$ fm and $\tau v' = 6$ fm as a thick solid curve.

maximum of the correlation curve and the slope for momenta above this maximum at the same time. This is also true for the heavy-ion study in ref. [5]. We therefore proceed in the analysis by assuming a finite lifetime τ. The present method does not allow one to directly measure this parameter (see eq. (3) and refs. [4,15]). Then the angle between $\boldsymbol{v}'$ and $\Delta\boldsymbol{p}$ becomes important. Koonin's program allows two limiting cases: $\Delta\boldsymbol{p}$ is parallel to $\boldsymbol{v}'$ and $\Delta\boldsymbol{p}$ is orthogonal to $\boldsymbol{v}'$. To check the importance of these two cases for the present experiment Monte Carlo simulations were performed assuming isotropic ^{2}He emission. A source velocity $v_0 = 0.03c$ was further assumed which corresponds to a source of 34 nucleons (see below). Because $v_0 \ll v'$ the results are not sensitive to this choice. The azimuth θ and the polar angle ϕ between $\boldsymbol{v}'$ and $\Delta\boldsymbol{p}$ were calculated as a function of the energy of the two protons. The results are also shown in fig. 2. The polar angle is almost zero. This indicates that both vectors lie in the reaction plane which is a result of the experimental setup which is symmetric to this plane. The mean azimuth in the area where two-proton correlations exist is $\theta = (15 \pm 15)^\circ$. From this Monte Carlo study we conclude that the two vectors are close to being parallel and not orthogonal to each other. Consequently, it was found impossible for the latter case to reproduce the present experiment although the two model parameters r_0 and $(\boldsymbol{v}'\tau)$ were varied over a large range. The calculation with the best agreement for the case with $\boldsymbol{v}'$ being parallel to $\Delta\boldsymbol{p}$ is also shown in fig. 3 which is consistent with the present detector geometry. The optimal choice for the size parameter was found to be 3 fm and 6 fm for $(\boldsymbol{v}'\tau)$. From the gaussian distribution parameter the radius of an equivalent sphere can be calculated as $R_e = \sqrt{\frac{5}{3}}\, r_0 = 3.9$ fm. In order to arrive at an estimate for the lifetime of the source we make the following simple scenario. If we assume that the volume is proportional to the number of nucleons contained in it with a density of $\rho = 0.138$ fm^{-3} then the source contains 34 nucleons which is approximately half of all nucleons in the composite system. For a velocity v' of the order of $0.2c$ which is typical for energetic particles a lifetime $\tau = 10^{-22}$ s is obtained. For particles from the low energy bin v' is typically $0.1c$ and hence $\tau = 2 \times 10^{-22}$ s.

These numbers of course can only give the order of magnitude. In the present experiment the source velocity is smaller than the ^{2}He velocity and consequently $\boldsymbol{v}'$ is dominated by the latter. This makes the result for the lifetime rather insensitive to the source size. We have therefore not analyzed the data with constraints on the ejectile energy. These data suffer from poor statistics because of the small particle multiplicity in the present light ion induced reaction. A detailed study of source sizes with respect to ejectile momentum is given in ref. [16] for heavy-ion induced reactions at higher beam velocities.

We summarize that we have measured two-proton correlations at small angles in a light ion reaction for protons being in the continuum. The data show final state interactions due to the attractive s-wave interaction. Selected data with protons of only low energies show almost no correlation because of the long lifetime. Even the anticorrelations at small relative momenta both due to Coulomb interaction and fermion statistics were absent. Data corresponding to large proton energies show a very strong correlation indicating a small source size. Analysis in terms of the Koonin model [4] yielded a statistically emitting source consisting of half of all nucleons and having a lifetime in the order of 10^{-22} s.

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