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Abstract : Two-proton coincidences at very small relative momenta were measured in the reaction $^{129}\text{Xe} + ^{48}\text{Ti}$ at 45 MeV/nucleon using the SPEG spectrometer at GANIL. From the experimental correlation function, a precise value of the lifetime $\tau_0 = (3.90 \pm 0.15) 10^{-21}\text{s}$ is extracted. Applying three angular cuts on the correlation function, a signature of directional effects is observed and a value of the particle source velocity $v_s = (0.27 \pm 0.03)c$ is deduced in case of a sequential equilibrium emission.

1. INTRODUCTION

Since several years, the two-proton correlation function has been extensively used in order to determine the dimensions of hot nuclei produced in the intermediate-energy heavy-ion reactions. The amplitude of the correlation is roughly determined by relative distance between the protons depending on both the relative position and the emission time difference. Thus, in the most general case, the correlation function probes simultaneously both spatial and temporal dimensions of the source. In order to overcome this ambiguity, two extreme situations have been studied where separately the radius (pre-equilibrium emission characterized by a negligible lifetime) and the lifetime (decay of an equilibrated nucleus) are the dominant parameters. However, in the second case, due to the lifetime effect, the correlation between the emitted particles is strongly attenuated and restricted to the low relative momenta. As a matter of fact, the region of very small momentum ($q < 10\text{MeV}/c$) allows one to precisely determine the lifetime while the intermediate range ($10\text{MeV}/c < q < 30\text{MeV}/c$) seems to be well suitable to study the relative weight of each effect giving rise to the correlations [1]. Unfortunately the experimental resolution often reduces the quality of the measured correlation function in this region implying a weak constraint on the theoretical predictions and thus a limited accuracy of the extracted parameters [2].

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Figure 1. Schematic views of the experimental setup in the horizontal plan (right part) and from the target (left part).

Figure 2. Energy loss in the first chamber versus total energy measured in the plastic scintillator. The dashed line represents an on-line cut in energy reducing the dominant contribution of single protons.

We have recently performed a measurement of two-proton coincidences covering, for the first time with a significant amount of statistics, an extended range of relative momenta from 1 to 100 MeV/c. Since the very low relative momenta region cannot practically be reached using a classical compact detector array, an original setup has been employed.

2. EXPERIMENTAL PROCEDURE

During the experiment, performed at the GANIL facility, a 45 MeV/nucleon $^{129}\text{Xe}(45^+)$ beam was used to bombard a $1\text{mg}/\text{cm}^2$ ^{48}Ti target. In order to limit the rate of random coincidences, the beam intensity was set to 50 nAe. In this reaction, studied in reverse kinematics, we were mainly interested in the detection of the light charge particles coming from the decay of a highly excited projectile-like emitter. The detection setup, centered at $\theta = 25^\circ$ in the laboratory frame, was composed of the magnetic spectrometer SPEG associated with twelve CsI(Tl) scintillators located in the reaction chamber (Fig.1). The spectrometer is characterized by a high resolution allowing an accurate determination of the angle and the momentum of the particles as required for a coincidence measurement. Moreover, it was used as a trigger of small relative momentum pairs selecting a very narrow region of the angular and energy distribution of the emitted protons (respectively defined by a solid angle of 4.9 msr and a momentum acceptance of $\Delta p/p = 7\%$). The spectrometer's magnetic rigidity was set to detect, on the nominal trajectory, protons with a kinetic energy of 30 MeV. The SPEG detection system, usually devoted to measure heavy residues, was adapted to detect light particles in coincidence. More precisely, we have used a plastic scintillator providing energy and time measurement and four drift chambers. An energy loss and three position signals were delivered by each chamber, tuned to extreme operating values in order to increase the efficiency of the proton detection [3].

3. RESULTS AND DISCUSSION

3.1. Construction of the experimental correlation function

The identification of protons was done using the residual energy signal provided by the plastic scintillator and the energy loss signals measured in each chamber. A good

Figure 3. Experimental correlation function (solid circles) measured in SPEG compared to the correlation function (open circles) predicted by the classical model for the mean lifetime $\tau_0 = 3.9 \cdot 10^{-21}$ s and convoluted with the response function of the spectrometer.

separation was obtained between the coincident and the single protons using the $(E, \Delta E)$ matrix (Fig.2). Applying geometrical conditions to the position signals delivered by each drift chamber, a final selection was performed. Then, based on the position measurements, the trajectories of the protons and their initial momenta were calculated [1].

From the two-proton coincidences measured in the spectrometer, the experimental correlation function was constructed covering the range from 1 to 10 MeV/c. The coincidence spectrum was corrected for a rate of 20% of random proton pairs deduced from a careful analysis of the single proton detection rate evolution during the experiment. The uncorrelated background spectrum was generated from pairs of single protons. The correlation function was finally normalized by setting equal areas of the correlated and uncorrelated spectra. A good resolution, of the order of 1 MeV/c, in the whole range of the relative momenta covered by the spectrometer results from a good position resolution (estimated at 3 mm) of the drift chambers.

3.2. Determination of the source dimensions

In order to extract the space-time dimensions of the emitting source we have compared the experimental correlation function to the predictions of a classical approach [4]. In frame of this model, three-body tridimensional trajectory calculations were performed describing two light charged particles sequentially emitted from a recoiling nucleus. The main characteristics of the source have been fixed assuming a projectile-like emitter and according to the experimental distributions and results obtained for similar reactions [5]: a mean charge and a mass equal to those of the projectile and a temperature equal to 4.5 MeV. One can note that by choosing a mean mass of the emitter we have fixed the size of the source. Nevertheless, in the case of sequential emission the predominant lifetime effect conceals the sensitivity of the correlation function to space dimensions.

A realistic comparison between experimental data and theoretical predictions requires the convolution of the theoretical correlation function with the response function of the SPEG spectrometer including its magnetic and resolution characteristics. Thus, the value of the mean lifetime of the hot nucleus was extracted taking advantage of the strong sensitivity of the coincidence spectra and the correlation function to the lifetime for very small relative momenta. With help of a χ^2 statistical analysis, the best agreement with experimental data was obtained with the mean lifetime $\tau_0 = (3.90 \pm 0.15) \cdot 10^{-21}$ s (Fig.3). From this large value one can conclude that the long-range Coulomb interaction is the most important source of the two-proton correlations measured in this experiment.

3.3. Directional effects

The information on the shape of the particle source as well as about the emission time can be extracted applying on the correlation function different angular cuts with respect to the pair motion. So far, despite several experimental studies no positive results have been obtained except for a recent experiment where such directional effects have been observed in p-p correlations in a non-equilibrium emission [6].

In case of a sequential equilibrium emission, a quantum model taking into account the quantum statistics and the final state interaction effects predicts a surprising result [7,1] : a strong suppression of the correlation in case of both extreme longitudinal ($\vec{q} \parallel \vec{v}$) and transverse ($\vec{q} \perp \vec{v}$) orientations of the relative momentum and the pair velocity (Fig.4). The suppression of the transverse configuration, sensitive to the space dimensions of the source, is well known and due to the antisymmetrization of the particle wave function. The effect predicted in the case of the longitudinal correlation function is more unusual and can be attributed to a directional dependance of the Coulomb interaction between the protons. However, the range, over the $\cos(\vec{q} \cdot \vec{v})$, of these two effects is different : the Coulomb interaction causes a smooth extended suppression while the quantum statistics effect is characterized by a sharp evolution over a reduced region around $\cos(\vec{q} \cdot \vec{v}) = 0$.

A similar study has been performed in frame of the classical model used to extract the source lifetime [4]. In order to investigate this effect, we have compared the experimental two-proton correlation functions, constructed for three gates of the relative orientation of the vector of momentum difference and the pair velocity, with the predictions of the classical description corrected for the SPEG resolution. The shape of the correlation function obtained for the longitudinal orientation clearly differs from those observed for the transverse and intermediate relative orientations, as expected by the classical approach (Fig.5). We should emphasize that the suppression for the transverse orientation, due to the antisymmetrization effects, predicted by the quantum model is washed out. Since the directional effects are the most pronounced when the angular cuts are made in the source rest frame, the particle source velocity v_s acted as a free parameter in this comparison. A fairly good agreement has been found between the experimental and the theoretical correlation functions and a value of the particle source velocity has been deduced : $v_s = (0.27 \pm 0.03)c$ which compares well with the data [8].

This result is the first signature of directional effects in particle correlations in the sequential decay of an excited source in statistical equilibrium. This kind of analysis provides a consistency check on the lifetime value extracted from the angular integrated correlation function and moreover it appears to be a powerful tool to determine the kinematic characteristics of the source.

4. CONCLUSIONS

We have presented the first results of an experiment performed in order to measure the two-proton correlation function at relative momenta smaller than 10 MeV/c. Coincidences of two protons emitted with almost equal momenta by an excited nucleus have been detected in the SPEG spectrometer. The experimental p-p correlation function was constructed, analysed and allows one to draw two main conclusions :

- By a realistic comparison with the predictions of a classical model, a precise value $\tau_0 = (3.90 \pm 0.15) 10^{-21} \text{ s}$ was deduced for the source lifetime.

Figure 4. Dependence of the theoretical p-p correlation function on the relative orientation between the velocity and the relative momentum of the pair predicted by quantum model for the lifetime $\tau_0 = 3.6 \cdot 10^{-21}$ s and four different values of the relative momentum

Figure 5. Experimental two-proton correlation function (solid circles) compared to the prediction of the classical model for the lifetime $\tau_0 = 3.9 \cdot 10^{-21}$ s and the source velocity $v_s = 0.27c$ (open circles), constructed for three different gates on the relative orientation of the vector of the momentum difference and the pair velocity : $\cos(\vec{q} \cdot \vec{v}) \in (0, 1/3)$ (a), $\cos(\vec{q} \cdot \vec{v}) \in (1/3, 2/3)$ (b), $\cos(\vec{q} \cdot \vec{v}) \in (2/3, 1)$ (c).

- For three different relative orientations of the velocity and the relative momentum of the proton pairs the experimental correlation function exhibits different shapes. The suppression observed for the longitudinal orientation, predicted by both quantum and classical approaches, is the first signature of directionnal effects in case of a sequential equilibrium emission. A quantitative agreement with the predictions of the classical model was found and the value $v_s = (0.27 \pm 0.03)c$ of the proton source velocity was deduced.

Twelve CsI(Tl) scintillators were used during the experiment. Events measured in these detectors will permit to construct the p-p correlation function at higher relative momenta and to undertake a comparative study with the unlike particle correlation functions. Finally, we want to stress that the SPEG spectrometer appears to be a powerful tool for a detailed analysis of the correlation function of identical particles at very low relative momenta. Therefore the combination of the sophisticated intensity interferometry method and the high technical qualities of the SPEG spectrometer offers a precious probe to characterize excited nuclei produced in heavy-ion reactions.

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