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Classical model for two-proton correlations in intermediate-energy heavy-ion reactions

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The Coulomb interaction between two protons sequentially evaporated from the same compound nucleus is studied as a possible origin for their measured correlations. This is done in the frame of three-body trajectory calculations with both Coulomb and nuclear forces. The temperature and mass of the emitting nucleus were determined from the measured energy spectra of single protons. The correlation function was found to be very sensitive to the mean time delay between the emissions of the two particles. A value $\tau_0=(1.0\pm0.2)\times10^{-21}$ s was obtained by comparison of our calculations with the two-proton correlation function measured at backward angles in the reaction ^{40}Ar+^{108}Ag at 44 MeV/nucleon.

I. INTRODUCTION

It is at present well established [1,2] that the shape of the correlation function for the emission of two like particles with small relative momenta $q < 50$ MeV/c during nuclear reactions contains valuable information about the spatial and temporal extension of their emission source. This is in analogy with photon interferometry used to measure the size of the stars [3] or with like-pion correlations used to measure the fireball in high-energy proton-proton collisions [4].

Unfortunately this information is difficult to extract since the shape of the correlation function is usually due to several, difficult to separate, effects. (a) The quantum statistical effect: When we deal with identical bosons (fermions) it is necessary to (anti)symmetrize their wave function and this leads to a constructive (destructive) interference between particles with small relative momenta $\mathbf{q}=\mathbf{p}_1-\mathbf{p}_2$. The deviation from unity ΔP of the detection probability of indistinguishable particles is of the order [1]

$$\Delta P=-\frac{1}{2}\cos\left[\frac{p_0}{h}d_0\theta\right],$$

where θ is the angle between the emission directions of the two particles, d_0 and $p_0\simeq p_1=p_2$ their separation distance and average momentum upon emission. For a typical simultaneous emission of two protons this leads to an anticorrelation for $q<20$ MeV/c. (b) The final-state-interaction effects: Unlike photons the outgoing charged particles interact through repulsive Coulomb forces and, when they are close to each other, also through attractive nuclear forces. The Coulomb interaction for instance causes a complete depletion (anticorrelation) of events for

$$q<\left[\frac{2\mu e^2Z_1Z_2}{d_0}\right]^{1/2},$$

where μ is the reduced mass. For $Z_1=Z_2=1$ and $d_0=6$ fm (an average nuclear radius) one obtains $q<14.2$ MeV/c.

On the contrary, the nuclear force produces an enhancement of events around $q=20$ MeV/c due to the attractive S-wave interaction between two protons.

For a simultaneous treatment of these effects a quantal approach is of course most appropriate [2] and it has been used to interpret the correlation of high-energy protons [5]. However, in order to have a solvable two-body problem the interaction between each proton and the emitting nucleus has been neglected in this type of calculation.

The three effects occur in the same range of relative momenta and it is therefore useful to look for a situation in which one of these effects can approximately be isolated. This is the purpose of the present paper. Two protons sequentially evaporated from a thermalized system will be mainly affected by Coulomb interaction [6,7]. At the moment of emission of the second proton, the first proton is far away so that one can neglect their nuclear interaction and, to some extent, the effect of the antisymmetrization of their wave function (no spatial overlap anymore). Indeed, for a nuclear temperature of 4 MeV and 10^{-21} s between the two emissions, $\langle d_0\rangle=43$ fm, $\langle p_0\rangle=87$ MeV/c and one obtains $\Delta P=0$ for $\theta>3°$. The effect of nonorthogonality of d_0 and p_0 was neglected in this estimate.

It is very probable that the conditions for such sequential evaporation have been experimentally fulfilled in a recent measurement of p-p correlation at backward angles in the reaction ^{40}Ar + ^{108}Ag at 44 MeV/nucleon [8,9]. These data were used for comparison with the present calculations and in this way an average lifetime of the emitting system was deduced. Lifetimes for particle emission at this intermediate bombarding energy are of particular interest since they help the understanding of the thermalization process and set the applicability limits for the statistical description of the very hot nuclei formed in this type of nuclear reactions. In high-energy heavy-ion collisions the interaction energy between the emitting nucleus and the protons can be neglected since it is much smaller than the energies of the emitted protons. This is no more justified in lower or intermediate-energy regimes where a three-body problem has to be solved.

The correlation function was therefore calculated based on a classical simulation for the dynamical evolution of the two protons and of the residual nucleus in their mutual Coulomb plus nuclear field. The formalism used is described in Sec. II. The initial conditions were selected, using the Monte Carlo method, from distributions compatible with the sequential evaporation hypotheses (Sec. III). The method of constructing experimental and theoretical correlation functions is explained in Sec. IV. In Sec. V the numerical results are presented, and Sec. VI contains the conclusions. A similar formalism (but without the inclusion of the nuclear interaction) has been used to calculate the p-p correlation function for the reaction $^{16}O + {}^{27}Al$ at a lower incident energy [7].

II. FORMALISM

To describe the separation of the reaction products for the sequential evaporation of two light charged particles from a residual recoiling nucleus, three-body bidimensional trajectory calculations have been performed. The two light particles were approximated by point charges and the emitting nucleus was supposed spherical.

This motion of the residual nucleus (index N) and of the light-particles (index 1 and 2) in their mutual field was calculated using the Lagrangian

$$L(x,y,\dot{x},\dot{y},t)=\begin{cases}\displaystyle\sum_{i=1,N}\frac{m_i}{2}\dot{r}_i^2-V_{1N} & \text{for } t<\tau\ ,\\ \displaystyle\sum_{i=1,2,N}\frac{m_i}{2}\dot{r}_i^2-\sum_{\substack{i,j=1,2,N\\(i<j)}}V_{ij} & \text{for } t\geq\tau\ ,\end{cases}\tag{1}$$

with the following notations:

$$\dot{r}_i^2=\dot{x}_i^2+\dot{y}_i^2,\quad i=1,2,N,$$

$$V_{12}=\frac{Z_1Z_2}{r_{12}},$$

$$V_{iN}=\frac{Z_iZ_Ne^2}{r_{iN}}-\frac{V_0}{1+\exp[(r_{iN}-r_0A^{1/3})/a]},\quad i=1,2,$$

and

$$r_{ij}=[(x_i-x_j)^2+(y_i-y_j)^2]^{1/2},\quad i,j=1,2,N.$$

τ is the time interval between the emissions of first and second particle. An attractive Woods-Saxon nuclear interaction V_0 was included only between the residual nucleus and each of the light particles but not between particles themselves since at the time τ (the birth of the second particle), of the order of 10^{-21} s, the first particle is much farther from the nuclear surface than the range of the nuclear interaction. Figure 1 shows the three-body problem which we are interested in and the geometry of

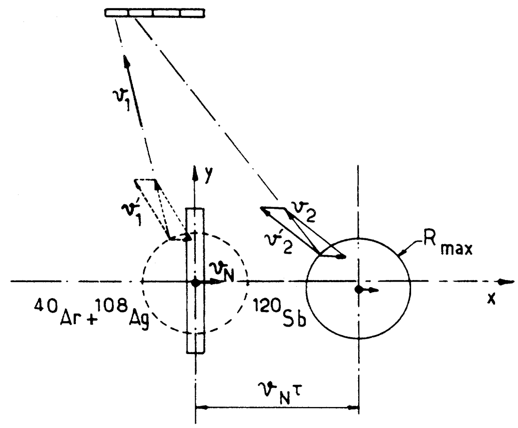

FIG. 1. Two particles are sequentially emitted from a residual nucleus (see text). The set of four detectors covering angles from 87.5° to 107.5° with respect to the beam axis is schematically presented.

the detection.

The restriction to one plane is justified in our case of intermediate bombarding energies since the recoiling emitters are strongly focalized around the beam direction [10]. Therefore, the detected events approximatively occur in the plane defined by the beam direction and the axis connecting the centers of the detectors, their azimuthal extension being less than 5°. It is also known that bidimensional trajectory calculations satisfactory describe the alpha-particle emission during nuclear fission [11] which is a similar process.

III. INITIAL CONDITIONS AND CHOICE OF PARAMETERS

The light particle was initially placed at the distance R_{max} (see Fig. 1) at any angle θ with respect to the beam direction. R_{max} is the position of the top of the barrier, i.e., of the maximum (V_{max}) of the interaction V_{iN} between the particle and the emitting nucleus. The emission was supposed isotropic and radial (relative angular momentum $l = 0$) with a maxwellian distribution for the initial particle energies (evaporation spectrum):

$$f(E_{1(2)})=\frac{E_{1(2)}-V_{max_{1(2)}}}{T^2}\exp\left[-\frac{E_{1(2)}-V_{max_{1(2)}}}{T}\right]\tag{2}$$

where T is the nuclear temperature. The initial energies $E_{1(2)}$ were selected randomly in the interval $[V_{max_{1(2)}}, E_{max}]$ from the above distribution using the Von Neuman algorithm. The emission through barrier penetration is therefore neglected on the basis of the high nuclear temperature involved here ($T=4$ MeV). Moreover, this assumption will be later justified by the agreement between the value of the average charge of the emitting nucleus necessary to reproduce the measured evaporation spectrum and a previous direct measurement of this same charge [10]. The magnitude of the initial velocities $v_{1(2)}$ was determined from their initial kinetic energies

$(E_{1(2)} - V_{\max_{1(2)}})$. Finally, the initial angles $\theta_{1(2)}$ were selected randomly in the restricted (by the geometry of the detection) interval [80°, 150°]. All above light-particle characteristics have been defined in the system of the emitter (residual nucleus).

As far as the characteristics of the residual nuclei are concerned, we have assumed a Gaussian distribution for their masses:

$$\omega(A) = \frac{1}{(2\pi\sigma_A^2)^{1/2}} \exp[-(A - A_0)/2\sigma_A^2] \tag{3}$$

and the following distribution for their recoil velocities:

$$g(v_N) = (v_N - \alpha)\exp(-v_N/\beta). \tag{4}$$

The coefficients in $g(v_N)$, $\alpha = 0.05$ cm/ns and $\beta = 0.6$ cm/ns, were fixed by reproducing approximately experimental inclusive velocity distributions of mass-identified residual nuclei as measured in the reaction ^{40}Ar + Ag between 39 and 60 MeV/nucleon at 10° in the laboratory system [10]. The mass characteristics, observed in this experiment, are in agreement with the chosen values of parameters of the distribution (3) which will be presented in Sec. V A.

Some of the parameters defining the initial conditions are related, like the charge of the emitter Z and its mass A ($Z = 0.425A$), by the assumption that, on the average, the number of preequilibrium neutrons and protons are equal.

At $t = 0$ the residual nucleus was placed in the center of the target ($x_N = 0$). Calculations were also done for $x_N = 3$ fm and $x_N = 10$ fm but no influence on the calculated correlation function was noticed.

The distribution of the time differences between the two emissions was taken in accordance with the radioactive decay law:

$$\rho(\tau) = \exp(-\tau/\tau_0). \tag{5}$$

The parameters V_0 and r_0 of the Woods-Saxon nuclear interaction between the emitter and the particle were taken from the analyses of the angular distribution in elastic scattering [12] while the parameter a was modified to reproduce the empirical fusion barriers [13]:

$$V_0 = 58.75 \text{ MeV}, \quad r_0 = 1.17 \text{ fm}, \quad a = 0.65 \text{ fm}.$$

The remaining parameters T, A_0, σ_A, and $E_{\max}$ were extracted from the energy spectrum of single protons (see Sec. V A).

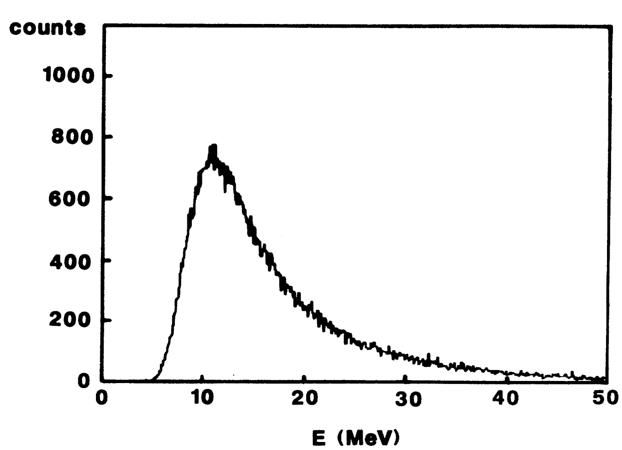

FIG. 2. Energy spectrum of single protons measured in the reaction ^{40}Ar + ^{108}Ag at 44 MeV/nucleon.

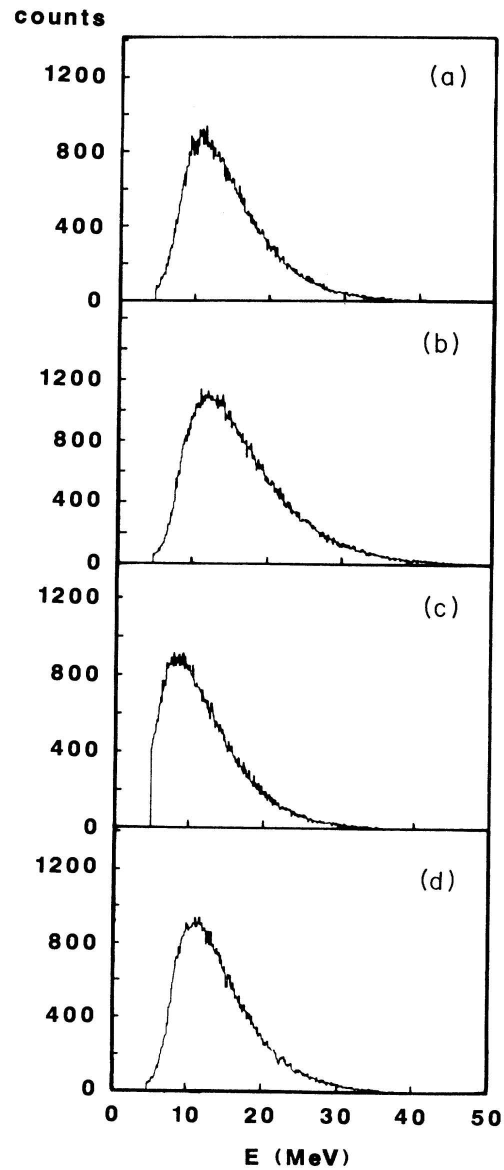

FIG. 3. Energy spectra of single protons calculated with different characteristics of the residual nucleus: the nuclear temperature T and the parameters of the Gaussian mass distribution (the mean value A_0 and the width σ_A) are (a) $T=4$ MeV, $A_0=120$ u, $\sigma_A=10$ u; (b) $T=5$ MeV, $A_0=120$ u, $\sigma_A=10$ u; (c) $T=4$ MeV, $A_0=90$ u, $\sigma_A=10$ u; (d) $T=4$ MeV, $A_0=120$ u, $\sigma_A=0$ u.

IV. CONSTRUCTION OF CORRELATION FUNCTION

Once the above initial conditions were chosen, the classical three-body trajectories were calculated. Then each particle was checked to see if it hit the set of four detectors covering angles form 87.5° to 107.5° with respect to the beam axis. Two types of events have been retained: (a) singles, at least one particle has hit a detector; (b) coincidences, two particles have hit the same or two separate detectors.

For each coincident pair a value of relative momentum q_c is calculated and a spectrum $C(q_c)$ is constructed. The single events provide a reference spectrum $S(q_s)$ without final-state interaction (i.e., correlation switched off at least in the angular range investigated). A relative momentum q_s is calculated for two particles from two successive single events. A two-particle correlation function $R(q)$ is defined as the ratio

$$1+R(q)=C(q)/S(q), \tag{6}$$

where $q=|\mathbf{p}_1-\mathbf{p}_2|/2$.

For both coincident and single events the relative momentum q can be calculated taking the exact particle positions. As can be seen in Sec. V B, this ideal correlation function contains interesting information but it cannot be directly compared to the experimental data. In fact, the experimental correlation function is generated in the same way as the calculated one but, because of instrumental constraints, the final particle position is the position of the detector center (90°, 95°, 100°, or 105°). Moreover, two particles in the same detector (true coincidence or two single successive events) cannot be taken into account. The last condition and a detection energy threshold (5 MeV for protons) impose a threshold for the minimum value of the relative momentum.

Therefore, the calculated correlation functions were always constructed in two manners: (a) using the exact final particle positions to provide the ideal correlation function (corresponding to infinitely small detectors), and (b) taking the positions of the detector centers and reject-

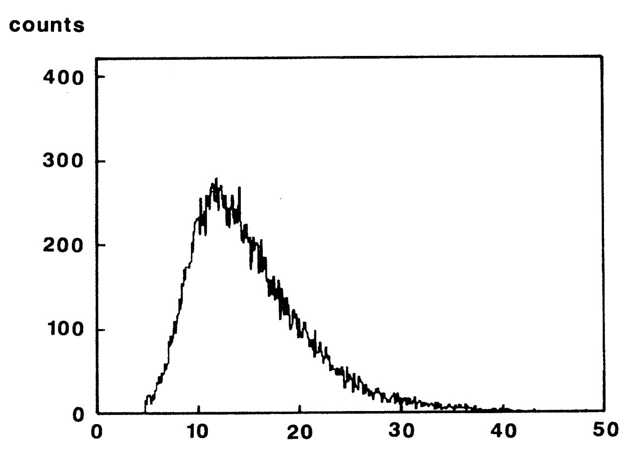

FIG. 4. Energy spectrum of single protons calculated with Coulomb interaction only between emitter and protons. $T=4$ MeV, $A_0=90$ u, $\sigma_A=10$ u.

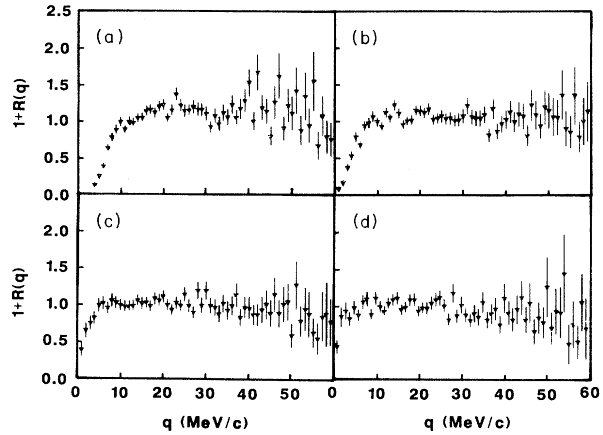

FIG. 5. Correlation functions calculated, using the exact final particle positions, for four different values of the time delay τ_0 between the emissions of first and second particle from the same residual nucleus ($T=4$ MeV, $A_0=120$ u, $\sigma_A=10$ u). (a) $\tau_0=5\times10^{-22}$ s, (b) $\tau_0=1.5\times10^{-21}$ s, (c) $\tau_0=5\times10^{-21}$ s, (d) $\tau_0=10^{-20}$ s.

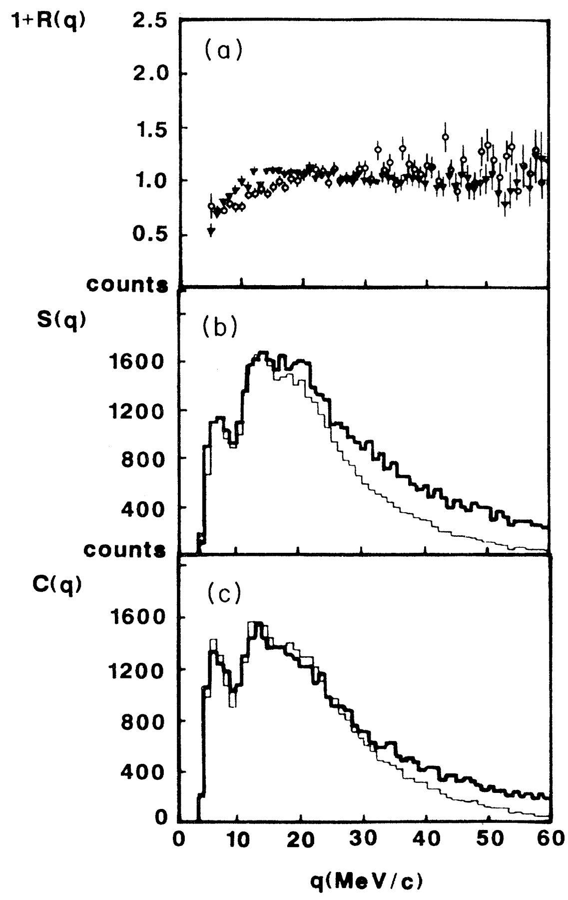

FIG. 6. (a) Correlation function measured at backward angles from 87.5° to 107.5° in the reaction $^{40}Ar + {}^{108}Ag$ at 44 MeV/nucleon (circles) and correlation function calculated, taking the positions of detector centers as the final particle positions, with the mean time $\tau_0=10^{-21}$ s (triangles). Corresponding measured (thick line) and calculated (thin line) spectra of (b) single $S(q)$ and (c) coincident $C(q)$ events (see text).

ing two particles hitting the same detector to compare them with the experimental data (corresponding to finite-size detectors).

V. RESULTS

A. Description of the particle-emitting system

Information about the residual nucleus is certainly contained not only in the correlation function, but also in the energy spectrum of the single protons. The experimental data [8] have been used (Fig. 2) to determine the nuclear temperature T, the maximum value of the kinetic energy $E_{\max}$, and the parameters of the Gaussian mass distribution of the emitter: the mean value A_0 and the width σ_A.

The calculated energy spectra of single protons are, in fact, very sensitive to the characteristics of the emitting system, namely, T and A_0 (Fig. 3). A good reproduction of the experimental average energy and of the width has been obtained by choosing $T=4$ MeV (the same value for the two emissions), $A_0=120$ u (the mass after emission of the first proton), $\sigma_A=10$ u, and $E_{\max}=60$ MeV [Fig. 3(a)] with remaining parameters given in Sec. III. It should be emphasized that we cannot reproduce the high-energy tail of the experimental spectrum with our single and thermalized source assumption. The most energetic particles reflect a short-lived nonequilibrated source giving rise to a small contribution at backward angles [14]. Consequently, this contribution will not affect significantly our approach to the long-lived type of the residual nucleus.

The value $A_0=120$ u (the error involved in this estimation is about ±3 u) implies a direct emission of about 13 charge units before thermalization which is in agreement with an independent measurement of the multiplicity of nonevaporative protons and alphas in the reaction Ar + Ag between 39 and 66 MeV/nucleon [10] as well as with estimation of pre-equilibrium emission with Landau-Vlasov calculations for the reaction Ar + Ag at 44 MeV/nucleon [9]. If the nuclear part in V_{iN} is neglected, a much too low value of $A_0(90\text{ u})$ is necessary to reproduce the single spectrum (see Fig. 4). This shows that, in order to characterize the emitting system reasonably well, the nuclear interaction has to be included in the calculation.

B. Correlation function

Once the main characteristics of the residual nucleus have been found we have analyzed the sensitivity of the calculated correlation function to the value of τ_0, the mean time between the two successive proton emissions. Correlation functions shown in Fig. 5 were calculated for four different values of τ_0 using the exact final-particle positions. We can notice a significant anticorrelation for

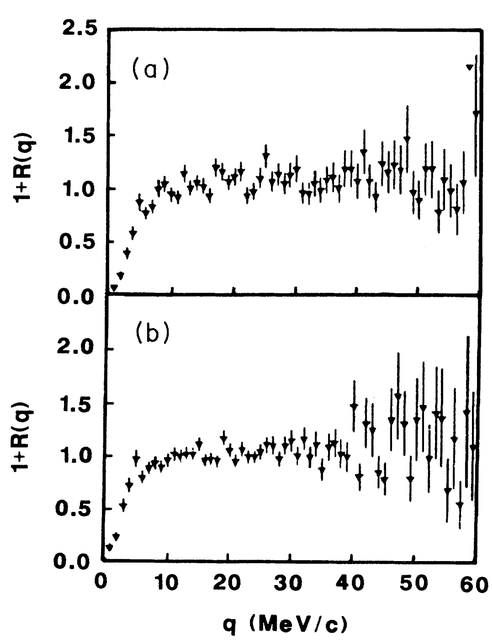

FIG. 7. Correlation function calculated with infinitely small detectors for two different mean values of the mass distribution of the emitter: (a) $A_0=60$ u and (b) $A_0=240$ u; remaining parameters: $T=4$ MeV, $\sigma_A=10$ u, $\tau_0=2\times10^{-21}$ s.

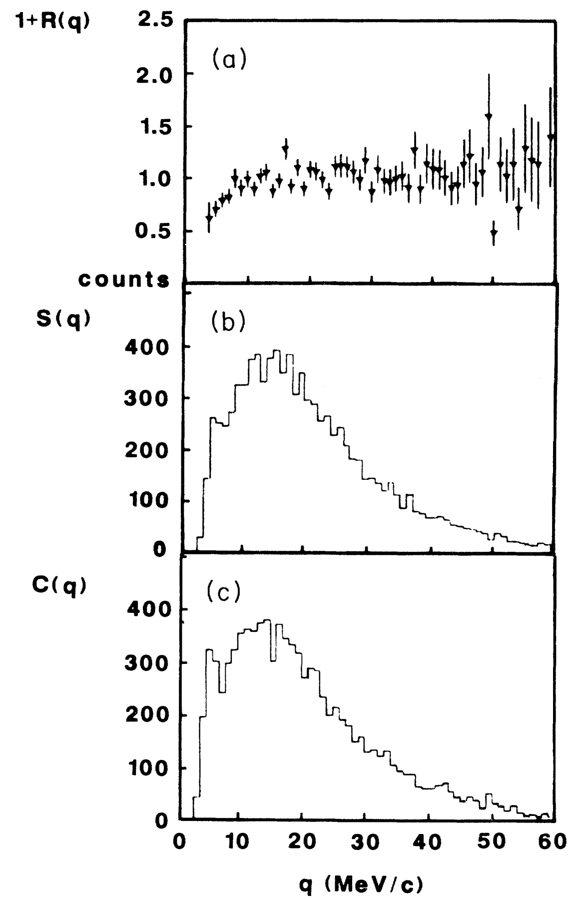

FIG. 8. (a) Correlation function and corresponding spectra of (b) single $S(q)$ and (c) coincident $C(q)$ events calculated with $A_0=60$ u and finite angular resolution; the other parameters are the same as in Fig. 7.

$\tau_0 = 5\times10^{-22}$ s and almost the loss of it for $\tau_0 = 10^{-20}$ s.

The experimental correlation function together with the corresponding spectra of single $S(q)$ and coincident $C(q)$ events (see Sec. IV) are presented in Fig. 6. The best reproduction of these data is obtained with the mean time $\tau_0 = (1.0\pm0.2)\times10^{-21}$ s. Resultant correlation function and coincident and single events spectra—all of them calculated taking the positions of detector centers—are shown for comparison in the same figure. This estimate of the mean time τ_0 gives only an upper limit for the lifetime of the residual nucleus since, in reality, a long deexcitation chain (with several protons and other particles) occurs. The experimental correlation function corresponds to any two (not necessarily successive) protons. In this sense the value 10^{-21} s is consistent with lifetimes predicted by the statistical model 5×10^{-22} [15].

The structures appearing in the spectra $S(q)$ and $C(q)$ reflect the geometry of the detectors with finite angular resolution (5°). A good reproduction of these structures as well as of the experimental momentum threshold (4 MeV/c) is due to a good reproduction of the measured proton energy spectrum. The high-momentum parts of the $S(q)$ and $C(q)$ spectra are due to the most energetic particles, because of the geometry of the detectors. Our model does not reproduce the high-energy tail of the proton energy spectrum (see Sec. V A), therefore it cannot reproduce the high-momentum part of the momentum distribution.

Finally, we would like to point out an interesting result: The characteristics of the emitter (A_0, σ_A, and T) have insignificant influences on the ideal correlation function, at least in this case of two identical particles that experience the same acceleration in the external Coulomb field. On the contrary, if the protons are measured with finite angular resolution, the choice of the emitter parameters strongly influence the result. Figures 7–9 compare results calculated with $A_0 = 60$ and 240 u with infinitely small (Fig. 7) and finite angular resolution detectors (Figs. 8 and 9). The dependence of the correlation function on the value of A_0 in Figs. 8 and 9 is seen to be due to the change in the position of the relative momentum threshold corresponding to two neighboring detectors. This minimum value of the relative momentum is equal to 3 MeV/c for $A_0 = 60$ u (Fig. 8) and 6 MeV/c for $A_0 = 240$ u (Fig. 9). The geometry of the detectors remains unchanged but the energy spectra of protons strongly depend on the value of A_0 (see Fig. 3).

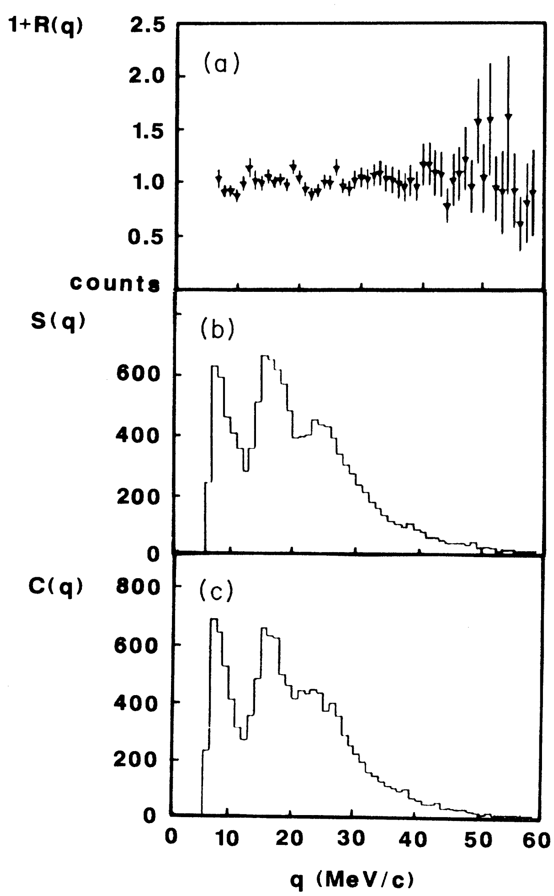

FIG. 9. The same as Fig. 8 but with $A_0 = 240$ u.

VI. CONCLUSIONS

Two protons sequentially evaporated from a thermalized system are strongly affected by the Coulomb interaction. In order to study this effect as a possible origin of measured correlation, three-body trajectory calculations with both Coulomb and nuclear forces have been performed. The data from recent measurements of two proton correlations at backward angles in the reaction ^{40}Ar + ^{108}Ag at 44 MeV/nucleon have been used for comparison with the present calculations. The main characteristics of the residual nucleus, i.e., its temperature $T = 4$ MeV as well as the mean value $A_0 = 120$ u and the width $\sigma_A = 10$ u of the Gaussian mass distribution, were determined by reproducing experimental energy spectra of single protons. To obtain relatively accurate values for these quantities it was necessary to include the nuclear interaction. The calculated correlation function was found to be very sensitive to the mean time delay between the emissions of two protons. The best reproduction of experimental data is obtained with $\tau_0 = (1.0\pm0.2)\times10^{-21}$ s, a value which, as far as considered as an upper limit for the emitting nucleus lifetime, is consistent with predictions of the statistical model. However, a slight difference between the slopes of the experimental and calculated correlation functions exists. It is probably due to the approximations used in the model, namely, to the neglection of the other particles in the deexcitation chain (except the two protons) and of the quantum statistical effects. Although a measurement with angular resolution better than 5° is necessary to estimate τ_0 more precisely, the imperfection of the experimental setup used here was proven to be sensitive to the characteristics of the residual nucleus.

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