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° Experiment performed at Laboratoire National GANIL

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Abstract : Correlations between light particles in ^{40}Ar induced reactions on ^{197}Au at E/A = 60 MeV have been measured in coincidence with a multidetector system. The correlations decrease monotonously with increasing charged particle multiplicity. With the help of a participant-spectator model, this multiplicity is tentatively connected to the impact parameter. The correlation function is analyzed in the framework of the final state interaction model in order to extract the space-time extent of the emitting source.

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In nucleus-nucleus collisions the concept of a locally heated zone (1,2) which would be the principal emission source of fast light particles, has been successfully used to explain the slope of inclusive light particle spectra (3). At relativistic energies the interaction or participant zone is restricted to the geometric overlap of the two nuclei (4). However, the validity of this concept can be questionable when the incident energy per nucleon is restricted to the Fermi energy domain. Recently, theoretical models based on a semi-classical transport equation including collision terms have been developed (5-7). Their results indicate that, except for very peripheral collisions, essentially all incoming nucleons participate in the collision.

From a model-independent point of view, any experimental proof of the localization of the interaction zone is of great interest. Information about the size of an emitting source can be obtained from light particle intensity interferometry (8), by measurement of the two-particle correlation function. Until now, investigations at intermediate energies have been limited to correlation functions derived from two particle inclusive data (9,10). In this letter, we present experimental measurements of the correlation between deuterons and alpha particles in coincidence with light particles detected at forward angles in a large multidetector system.

The experiment was performed at the laboratoire National GANIL in Caen (France). A gold target of 10 mg/cm^2 areal density was irradiated by an ^{40}Ar beam at an incident energy of E/A = 60 MeV. Light particles ($Z<3$) were detected by a closely packed hexagonal hodoscope (9) consisting of 13 Si-NaI (400 µm and 10 cm thick) telescopes. The angular separation between adjacent elements was 4.2 deg, each telescope subtending a solid angle of 0.46 msr. This hodoscope was centered at a laboratory angle of 30 deg with respect to the beam direction. The energy calibration for isotopes with $Z \leq 3$ is accurate to within 1.5%. In order to select on event-type, coincident light particles were detected in a multidetector consisting of 96 2mm-thick plastic scintillators (plastic wall) (11) arranged in a circular array of seven rings around the beam axis. The whole plastic wall covers an angular range of 3 deg $\leq\theta\leq$30 deg in the laboratory frame. Some plastic detectors, in the outer two rings, were shadowed by the hodoscope and were not taken into account in the analysis. Because of a very high counting rate due to elastic events in the inner ring, only the six outer rings were used so that the minimum detection angle was 5 deg. The charge and the velocity of each light particle were determined by a ΔE-time of flight measurement. The detection threshold in the plastic wall was about 4 MeV/nucleon for protons and alpha particles. This is significantly below the corresponding average kinetic energies observed in this experiment.

The data taken with the hodoscope are presented in terms of the correlation function R(q), which is defined for a particle pair (1,2) by

$$Y_{1,2}\,(p_1,\,p_2) = C*Y_1(p_1)\,*Y_2\,(p_2)*(1+R(q)) \qquad (1)$$

where $Y_{1,2}$ denotes the coincidence yield, Y_1 and Y_2 the single yields. The laboratory momenta of particle 1 and 2 are p_1 and p_2 respectively, and q is the momentum of relative motion. The normalization constant C is determined by the requirement that R(q) = 0 at large relative momenta ($150<q<200$ MeV/c). The experimental correlation function is obtained by inserting the measured yields into Eq. 1 and summing both sides of the equation over all energies and angles corresponding to a given value of q. The detection thresholds for d and α are 15 MeV and 35 MeV, respectively. At 30°, these detection thresholds exclude significant contributions from the sequential decay of projectile and target residues produced in quasi-elastic reactions. For event-selection using the plastic-wall, the same constraint is applied to both the coincidence and single yields. The experimental d-α correlation function without any constraint is displayed in fig.1a. A detailed discussion of this correlation function has been given in ref. 9.

Coincident data from the plastic wall provide information concerning the degree of violence of the reaction. In the present letter, we explore the effects of the observed charged particle multiplicity (O.M) on the light particle correlations. The measured d-α correlation function under the constraint that no particle is detected in the plastic wall, is presented in fig. 1b. An enhancement of the correlation by a factor of 1.7 is observed with respect to the ungated one. In contrast, the selection of d-α events in coincidence with high O.M. (fig. 1c) reduces the correlation by a factor of 3. Between these two extremes, the maximum of the correlation function decreases smoothly with increasing multiplicity as shown in fig. 2a. Similar trends are also observed for p-p, p-α, α-α, d-^{3}He, p-^{7}Li correlation functions measured in this reaction.

Calculations of the d-α correlation function (12), based on the final state interaction model of Koonin (8) for complex light particles are presented in fig. 1a. In this model, the two coincident particles are supposed to be emitted independently from a source with a given space-time extent, and to interact as two free particles. For the present calculations, a source of gaussian spatial density and negligible lifetime is assumed. The finite angular and energy resolution of the hodoscope are taken into account. Details on the calculations are given in ref. 12. Since zero lifetime is assumed, it has to be noted that the extracted values of r_0 are maximum values, because a finite lifetime would reduce the correlation. The source radius parameter r_0 extracted from the d-α correlation function increases by a factor of 2 between the two extreme values of O.M. (fig. 2b). A similar trend has already been observed for p-p correlations at higher incident energy (13). The largest value of r_0 = 8.0 fm, obtained for the largest O.M. corresponds to a matter distribution with a root-mean square radius of 9.8 fm, significantly larger than the root-mean square radius of a system formed by all incoming nucleons. This indicates that the desintegration of the system occurs either at a reduced density ($\sim 0.5\rho_0$) or over a non negligible time interval.

To facilitate the interpretation of these data and because of the restricted solid angle of the plastic wall, one would like to establish that the O.M. varies monotonously as a function of the total charged particle multiplicity, considered as an indication of the impact parameter. A Monte-Carlo simulation can give the dependence of the O.M. on the impact parameter. The reaction model used for this calculation is the abrasion-ablation model as extended by Dayras et al. (ref. 14) to take into account the cohesion forces in nuclei. This model reproduces in the Fermi energy domain the inclusive and coincidence data concerning mainly the projectile- and target-like fragment properties. It also predicts the velocity, excitation energy and number of nucleons for projectile-like, target-like and participant sources as a function of the impact parameter. In the simulation code, the sources are supposed to emit particles isotropically in their reference frame according to a thermal energy distribution. The mass and atomic number of the evaporated particles are randomly chosen according to the experimental relative yields. The exact geometry of the plastic wall as well as shadow effects are taken into account.

In fig. 3, the predicted yields in the wall are presented as a function of the O.M. for two impact parameters b = 10 fm (full line) and b = 1fm (dashed line). They are compared to the experimental multiplicity spectrum (data points). As expected, high O.M. are only achieved in central collisions, while low O.M. are essentially fed by peripheral collisions. From central to peripheral collisions, the O.M. decreases monotonously. Thus we deduce from fig. 1 that central collisions give rise to suppressed correlations, while peripheral collisions show enhanced correlations.

In the Fermi energy regime, semi-classical calculations (5-7), taking into account nucleon-nucleon collisions as well as mean field effects, do not indicate any important increase of the size of the interacting zone with decreasing impact parameter. From the above results, one could suggest that the large observed variation of the parameter r_0 does not reflect only a simple spatial effect, but also mocks up an impact parameter dependence of the lifetime of the emitting zone. According to Koonin (8), this lifetime is comparable to the collision time , which is strongly impact parameter dependent. This explanation could be connected to the variation of r_0 with the total kinetic energy of two coincident particles, as observed in (15) : the fastest particles are expected to be emitted earlier, when the relative velocity is still large.

However, there are limits to the extent that a direct relationship between participant volume and impact parameter can be established. Even if simulations indicate that the O.M. is very sensitive to impact parameter for values between b = 1 fm and b = 10 fm, fluctuations in the O.M. will reduce this sensitivity. Furthermore, the separation of the colliding system between participant and spectator nucleons may be oversimplified at the considered incident energy.

None of these reservations, however, change appreciably the main observation of this work : there is an unmistakable reduction in the space-time localization of the emission of coincident particles and smaller subsystems are observed at larger impact parameters where fewer nucleons are violently interacting. It is the first time in this energy domain that such a drastic variation of the correlation pattern is observed, pointing to its extreme sensitivity to the collision time and volume upon the impact parameter.

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FIGURE CAPTIONS

Figure 1 : d-α correlation function versus relative momentum q :
a) without any selection in the plastic wall
b) for zero multiplicity (M=0)
c) for M = 10
Equally shown are theoretical calculations (12) for r_0 = 4,6 and 8 fm.

Figure 2 : Evolution of the maximum of the d-α correlation function (a) and the derived space-time parameter r_0 (b) as a function of the detected multiplicity.

Figure 3 : Comparison between the experimental multiplicity spectrum (data points) and the multiplicity spectra predicted by the Monte-Carlo simulation described in the text for b = 10 fm (full line) and b = 1 fm (dashed line).

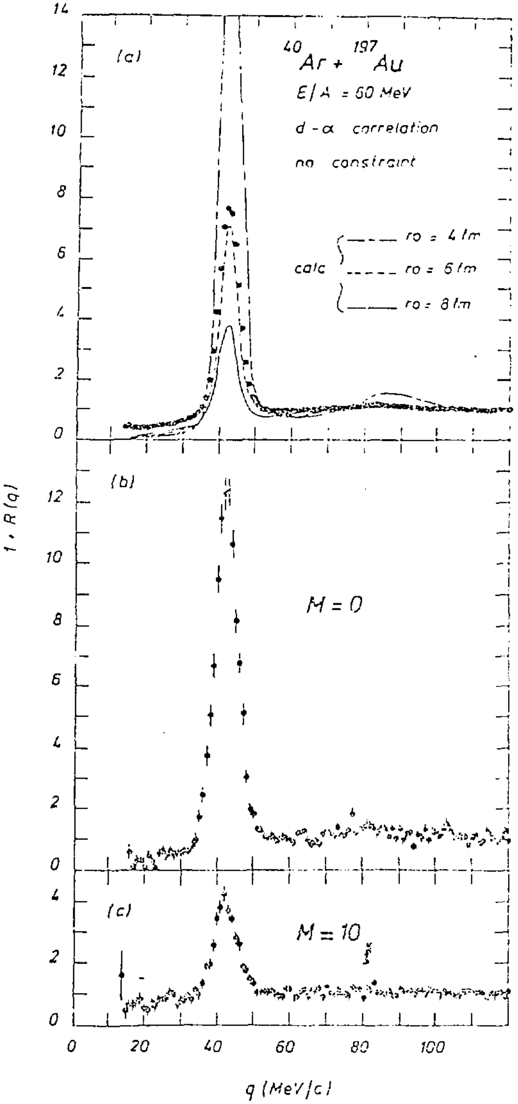
(a)
$^{40}Ar + ^{197}Au$
E/A = 60 MeV
d - α correlation
no constraint
calc
ro = 4 fm
ro = 6 fm
ro = 8 fm
(b)
M = 0
(c)
M = 10
1 + R(q)
q (MeV/c)
0
2
4
6
8
10
12
14
0
20
40
60
80
100

Figure 1

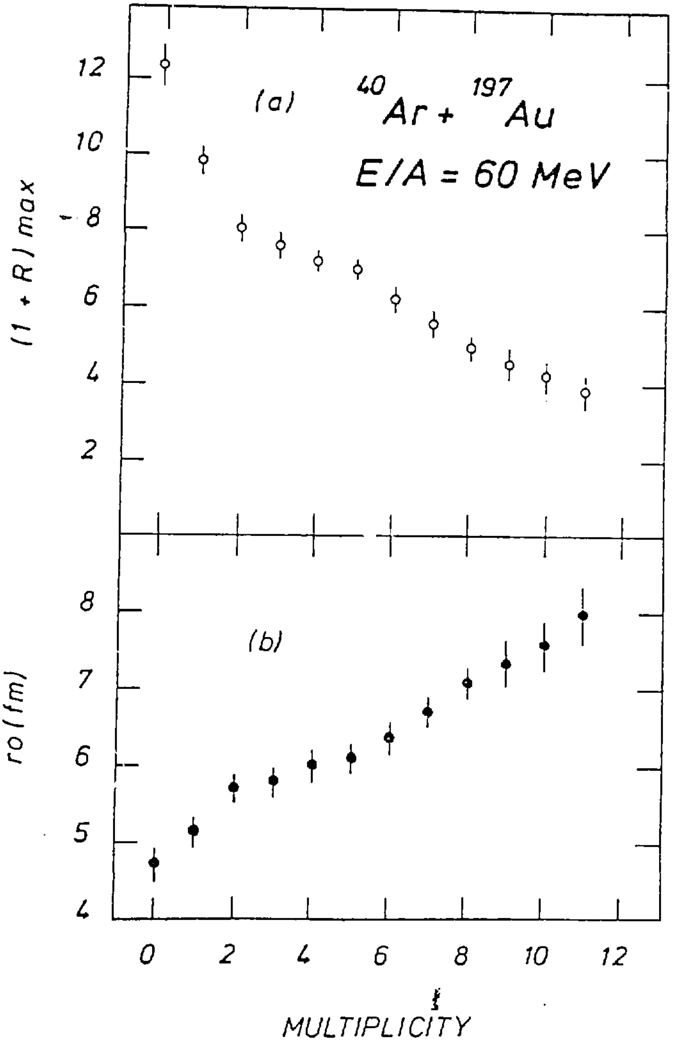
(a)
$^{40}Ar + ^{197}Au$
E/A = 60 MeV
(1 + R) max
12
10
8
6
4
2
(b)
ro (fm)
8
7
6
5
4
0
2
4
6
8
10
12
MULTIPLICITY

Figure 2

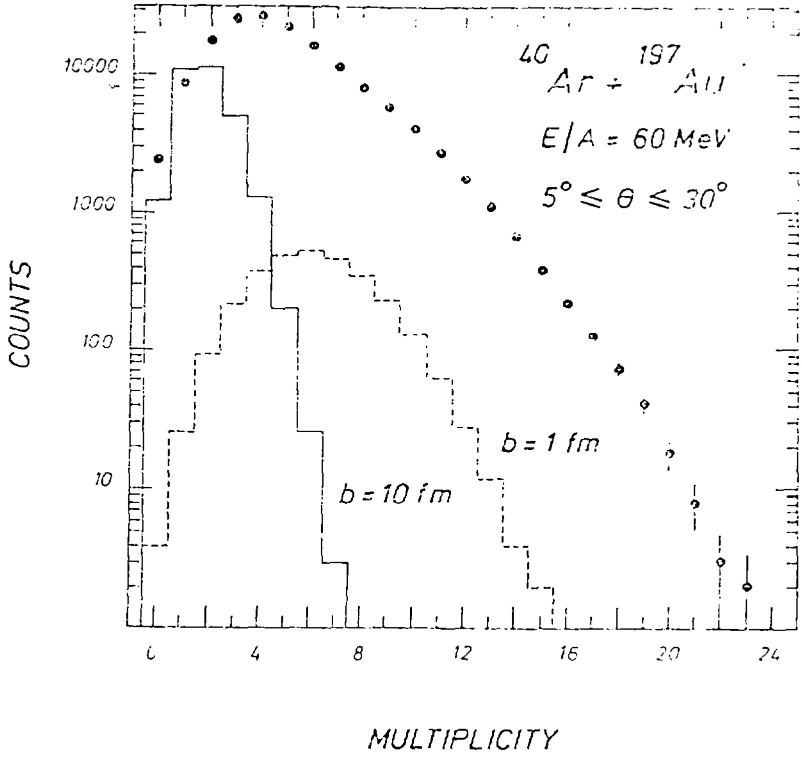
$^{40}Ar + ^{197}Au$
E/A = 60 MeV
5° ≤ θ ≤ 30°
COUNTS
10000
1000
100
10
b = 1 fm
b = 10 fm
0
4
8
12
16
20
24
MULTIPLICITY

Figure 3