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BINARY ASPECTS AND PARTICLE MULTIPLICITIES
OF THE FRAGMENTS FROM $\text{natAg} + 340 \text{ MeV } ^{40}\text{Ar}$
DEEP INELASTIC COLLISIONS*

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ABSTRACT

Deep inelastic fragments from the reaction $\text{natAg} + 340 \text{ MeV } ^{40}\text{Ar}$ have been studied in coincidence. Charged particles ($10 \leq Z \leq 32$) were detected and identified in Z by means of a ΔE -E telescope, while the complementary fragments were detected in a one-dimensional solid state position-sensitive detector. Both in-plane and out-of-plane correlations were measured. The results confirm the binary nature of the deep inelastic process for this reaction. From the measured energies and angles of the fragments and the atomic number of one of the fragments, it was possible to determine the total mass loss due to the de-excitation of the fragments as well as the total evaporated charge at symmetry. An iterative procedure is discussed which enables one to determine the masses and kinetic energies of the fragments before evaporation, as well as the total number of particles evaporated by each fragment. The widths of the in-plane and out-of-plane correlations agree with the results of the iterative calculations, as do evaporation calculations which are based on the charge equilibrium model. The experimental results support the charge equilibrium model and indicate that thermal equilibrium is achieved between the fragments at fixed mass asymmetry.

E NUCLEAR REACTIONS $\text{nat}_{\text{Ag}}(^{40}\text{Ar}, Z)$;
 $E = 340 \text{ MeV}$; studied binary events
 $10 \leq Z_3 \leq 32$; deduced masses of
 fragments before evaporation and mass
 loss due to evaporation.

INTRODUCTION

Heavy ion studies have shown the existence of a new class of reactions, generally called deep inelastic collisions (DIC). In the exit channel these reactions are characterized by the emission of fragments over a broad range of masses and kinetic energies, and by angular distributions indicative of a much shorter lifetime than would be expected from compound nucleus decay. The fact that the kinetic energy of the outgoing fragments approximately corresponds to the Coulomb energy of two spherical fragments in contact is part of the indirect experimental evidence [1] that the process is indeed essentially binary, leading to two highly excited fragments.

During the interaction time, the "intermediate complex" formed by the two nuclei tends to equilibrate in its various degrees of freedom. Some of them, like the mass asymmetry, have very long relaxation times, and do not equilibrate before the decay of the system. The angular distributions and mass distributions experimentally obtained for a broad range of combination of targets and projectiles do, in fact, indicate that compound nucleus equilibrium is not achieved for this degree of freedom. These experimental angular and mass distributions are well understood in terms of the diffusion model [2,3]. Some other degrees of freedom appear to equilibrate very quickly like the neutron-to-proton ratio of the fragments and the relative motion of the target and projectile [1,4]. The relaxation of the latter mode leads to the dissipation of the entrance channel kinetic energy.

After the break-up of the intermediate complex, the fragments are highly excited and are expected to emit neutrons, protons and

α -particles through the evaporation process. A detailed investigation of the charges and masses of the fragments, as well as their charge and mass loss through evaporation, allows one to learn about the relaxation of other degrees of freedom, like the sharing of the excitation energy between the two fragments. In the following we describe a coincidence experiment performed on the system Ar + Ag at 340 MeV bombarding energy in which the measurement of the Z of the light fragment along with the energies and angles of both fragments permits the determination of the masses before evaporation, as well as insight into the evaporation process itself.

In the first section the experimental technique is described. The second section deals with the energy and angle calibration scheme. In section three the results of the in-plane experiment are presented and are compared with evaporation calculations. The widths of the in-plane and out-of-plane correlations are discussed in the fourth section. In the fifth section cross section data are given. The conclusions are summarized in the last section.

1. EXPERIMENTAL SET-UP

The ^{40}Ar beam from the SuperHILAC at an energy of 340 MeV was used to bombard a natural, self-supporting, $350\text{ }\mu\text{g}/\text{cm}^2$ Ag target. Two detector systems measured simultaneously the light and heavy fragment energies and angles. The light fragment detector, which consisted of an ionization chamber telescope [5], measured both the energy (E_3) and the atomic number (Z_3). This telescope was placed at 42° with respect to the beam direction. The thin window ($40\text{ }\mu\text{g}/\text{cm}^2$) of the ionization

chamber was mounted on a collimator with a small diameter (3mm), thus permitting the determination of the angle of the detected fragments to $\pm 1^\circ$. The atomic numbers of the fragments were resolved up to $Z_3 = 32$, which corresponds to the splitting closest to symmetry. On the other side of the beam axis, a high resistivity silicon position-sensitive detector (PSD), spanning 17° in its largest dimension and 2.6° in its smallest, was placed in the reaction plane, successively at 30° and 50° from the beam axis, thus exploring the $20^\circ - 60^\circ$ in-plane distribution of the correlated heavy fragment. The measured quantities were the energy (E_4) and the in-plane angle (θ_4) of the heavy fragment. Out-of-plane angular distributions were also measured (keeping the light fragment telescope at a fixed angle of 42°) by placing the PSD vertically at three different radial angle settings (29° , 42° , and 50°).

Figure 1 shows the chamber configuration. On this drawing some of the symbols used in this paper are defined. The electronic chain of equipment for each detector (ΔE_3 , E_3 , position, and E_4) consisted of a preamplifier, amplifier and linear gate. These gates were opened by a coincidence requirement between the telescope and PSD. The fifth chain consisted of a time-to-amplitude converter which measured the time difference between the ionization telescope (E_3 signal) and the position-sensitive detector (E_4 signal). These five signals were written on magnetic tape in an event-by-event format via an analog-multiplexer, analog-to-digital converter system and a PDP-15 computer.

2. ENERGY AND ANGLE CALIBRATION

Accurate measurements of the laboratory energies and angles of both the binary fragments originating from the break-up of the

"intermediate complex" are required in order to determine such quantities as the mass of the fragments before evaporation and the number of particles evaporated from these fragments. Accuracy in these measurements is required because the pre-evaporation masses are determined indirectly from two body kinematical laws, and the number of evaporated particles through the deviations of the experimental energies and angles from these laws.

The PSD detector was operated at a voltage four times higher than that recommended for this type of detector in order to minimize the recombination effects which are the major cause of the pulse height defect. (This voltage was below the onset of charge multiplication.) In addition, a 4 μ s delay line shaping time was used for the energy signal. This signal was sampled 2 μ s after the leading edge in order to minimize the variable rise time effects associated with different resistive paths to ground for different positions of the ions entering the PSD.

The angular calibration of the PSD was performed using a 7-hole mask and Ar ions elastically scattered from a thin gold target. The intrinsic linear resolution of the PSD is of the order of 1 mm, which corresponds to an angular resolution which is better than one degree for our setup. The measured energies in both detectors were corrected for the energy loss in the target and in the thin entrance window of the telescope and the pulse height defect as described in the next section.

2.1. Pulse height defect corrections

The pulse height defect (PHD) denotes the difference between the true energy and the apparent energy of a charged particle detected in a counter.

While the effect in silicon is very small for low-Z ions, it is significantly larger for high-Z ions of the same kinetic energy. This effect is due primarily to particle-hole recombination, the rate of which increases with the ionization density, and, in particular, becomes a serious problem in high resistivity silicon detectors.

A separate experiment was performed in order to calibrate our solid state detectors. In this calibration experiment a beam of 163 MeV Ar from the 88" LBL cyclotron impinged on thin (200 to 350 $\mu\text{g}/\text{cm}^2$) self-supporting foils of natural gold, silver and copper. The incident projectile energy was below the Coulomb barrier for gold and very near the Coulomb barrier for silver, thus minimizing the possibility of contaminating the elastic peak with transfer products. The observed energies of the elastically scattered nuclei were corrected for energy losses in the detector dead layers, target and window using the range-energy relations of Northcliffe and Schilling [6]. The corrected energies were then compared to the calculated elastic energies of both nuclei and the differences were attributed to the PHD. The PHD for gold, silver and copper ions in the high-resistivity silicon of the PSD is plotted in Fig. 2 as a function of the energy of the ion as it enters the silicon. The energy units (LSS units) defined by Lindhard, Scharff and Schiott [7] have been used in order to express the pulse height defect of any ion in the same medium in terms of a single function of the ion energy. The PHD is approximately linear with the stopping power so that the relationship between energy in MeV (E) and LSS (ϵ) units is a function of the Z and A of the ion in the stopping medium. This relationship for an ion stopping in silicon is:

$$\epsilon = E \frac{6.525 \times 10^4 (Z^{2/3} + 5.809)^{-1/2}}{Z(A + 28.09)}$$

A single, empirically-determined [8] function of the form

$$\Delta\epsilon = \text{PHD} = \frac{6 \epsilon}{\epsilon + B_1} + \frac{B_2}{1 + 500 \epsilon^{-1.4}}$$

has been used to express the PHD in LSS units. In this way a single universal function can then be fitted to all of the PHD data obtained with a given detector. Figure 3 is a plot of the PHD data from Fig. 2 in LSS units. A fit to the data with the empirically determined function gives values of 25. for B_2 and 15. for B_1 . A similar technique applied to the silicon surface barrier detector used in the ΔE -E telescope gave values of 18. for B_2 and 8. for B_1 , in agreement with previously determined [8] parameters for detectors of this type. The resistivities of the PSD and the surface barrier detectors are approximately 25,000 ohm-cm and 4000 ohm-cm respectively.

A critical test of the consistency of the energy corrections for heavy ions is the ability to reproduce the kinematics of elastic scattering. The results of correlated elastic scattering measurements made with 163 MeV argon incident on gold, silver and copper targets are shown in Fig. 4. In all cases, the PSD was used to detect the recoiling target nuclei. The agreement with calculations (solid lines) is good. The agreement obtained

indicates that our calibration scheme is self-consistent, and can be confidently applied to the results obtained for deep inelastic processes over the same energy range.

3. IN-PLANE EXPERIMENT

3.1. Kinetic energies

Previous experiments [9] on the system $^{nat}\text{Ag} + 340 \text{ MeV } ^{40}\text{Ar}$ performed without a coincidence requirement (singles) showed two peaks in the kinetic energy spectra. The higher energy peak is associated with the so-called quasi-elastic, or partially relaxed reactions, which predominate at angles close to the grazing angle for fragments with atomic numbers close to that of the projectile. In the present experiment the angle setting (42° lab) of the light fragment telescope was far removed from the grazing angle (18° lab). Consequently, only the relaxed component appears in the energy spectra shown in Fig. 5 for fragments of various Z. Representative error bars are given for the coincidence data. The area of the coincidence peak was normalized to the area of the singles data. Both mean values and widths are equal, indicating that the coincidence requirement does not introduce any bias or single out any special kind of events.

3.2. Angular correlations

If the intermediate complex undergoes binary splitting, the angular distribution of the correlated heavy fragment should be peaked around an average angle $\bar{\theta}_4$ imposed by two body kinematics. This behavior is observed in Fig. 6 which shows some typical angular correlations for

the heavy partner in coincidence with a light fragment for some selected Z-values. In the vicinity of $Z = 15$, the correlations were measured in two successive angular settings of the PSD. For atomic numbers above 20, the full angular correlation was recorded in a single setting except for the very highest Z's, where the correlation extended somewhat beyond the limits of the detector. The arrows in Fig. 6 are calculated neglecting evaporation and assuming that the kinetic energies arise from Coulomb repulsion of two spherical fragments separated by a distance of 2 fm ($r_0 = 1.23$ fm). The approximate agreement between the calculated angles and the centroids of the experimental angular distributions indicates that the events recorded in coincidence arise from a binary break-up of the composite system. The width of the angular correlation appears to be fairly constant with Z. This width is partly due to recoil effects associated with particle evaporation from the fragments, and partly to kinematical effects arising from the natural spread of the light fragment energy. This decomposition will be discussed in a later section.

3.3. Correlation of energies and angles

The correlated distributions of E_3, θ_4 and E_4, θ_4 corresponding to $Z_3 = 20$ are shown in Fig. 7a and 7b, respectively. In the case of a binary break-up of the intermediate complex, the conservation of linear momentum and of mass can be expressed through the following set of equations in the lab system:

$$E_3^* A_3^* = A_1 E_1 \frac{\sin^2 \theta_4}{\sin^2(\theta_3 + \theta_4)} \quad , \quad (1)$$

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$$E_4^* A_4^* = A_1 E_1 \frac{\sin^2 \theta_3}{\sin^2(\theta_3 + \theta_4)}, \quad (2)$$

$$A_3^* + A_4^* = A_1 + A_2 \quad (3)$$

Symbols are defined in Fig. 1. In Eqs. (1-3), and in all that follows, an asterisk * is used to indicate pre-evaporation quantities.

For all the atomic numbers considered in this experiment, the sum of the two fragment angles in the lab system is close to 90° ($Z_3 = 10$, $\theta_3 + \theta_4 = 70^\circ$; $Z_3 = 32$, $\theta_3 + \theta_4 = 100^\circ$). The laboratory system is therefore a convenient system of reference for a qualitative inspection of the data since the correlation between all the variables (E_3 , θ_3 , E_4 , θ_4) simplifies because the denominator in Eqs. 1 and 2 is approximately constant and close to unity. For instance, to a good approximation the energy of a fragment depends only on the angle of emission of the complementary fragment. The knowledge of the mass of this fragment after the scission point and before evaporation $A_{3,4}^*$ would then determine completely its kinetic energy $E_{3,4}^*$.

Several experiments [4,10] have shown that charge equilibration in DIC is a very fast process, even faster than the kinetic energy dissipation of the projectile. Since the telescope was far removed from the grazing angle, thus selecting reactions with relatively long interaction times, the neutron to proton ratio $\frac{N}{Z}$ is expected to be equilibrated between the two fragments. The solid lines of Figs. 7a and 7b represents the E_3^* , θ_4 and E_4^* , θ_4 correlations expected for a two body process (Eqs. 1 and 2).

The masses used in these equations were calculated from the measured Z of the light fragment (assuming no charged particle evaporation) and the $\frac{N}{Z}$ of the compound system. Despite the evaporation, which considerably scatters energies and angles, the data for both the light and the heavy fragment follow the trend of the expected correlation in support of the two body hypothesis, although the average energies are significantly lower. This can be seen more quantitatively if the events of Fig. 7b are separated in two populations. In Fig. 8 we compare the reduced energy distributions for $Z_3 = 20$ corresponding to events with $\theta_4 < \bar{\theta}_4$ and events with $\theta_4 > \bar{\theta}_4$, where $\bar{\theta}_4$ represents the most probable value ($\bar{\theta}_4 = 46^\circ$ for $Z_3 = 20$). For $Z_3 = 20$ the mean value of the sum of the two fragments angles is $\theta_3 + \theta_4 = 89^\circ$. Equation 2 then predicts that the energy E_4^* must be approximately independent of the θ_4 angle. The experimental data seem to follow the two body prediction since mean values and variances of the two distributions of Fig. 8 are the same within the statistical errors.

Since the incident energy is well above the Coulomb barrier, the fragments are highly excited. If we assume that the main evaporation process takes place when the fragments are already separated, the difference between the first moment of the E_4 distribution (with no constraint on θ_4) and the two body prediction (using Eq. (2) and the mass $M_4^* = (Z_1 + Z_2 - Z_3) \left(\frac{M}{Z}\right)_{\text{c.m.}}$) is proportional to the number of nucleons evaporated by the heavy fragment since, on the average, the velocity of the fragment is unaltered by isotropic emission of particles. This energy difference of about 5 MeV corresponds to a number of 8 nucleons evaporated by the heavy fragment. Of course, in this analysis this number

is very dependent on the choice of the initial mass M_4^* of the fragment. In the following sub-sections more general approaches are described to obtain the number of evaporated particles which do not make assumptions about the masses of the fragments before evaporation.

3.4. Analysis of the average values of the distributions

The following analysis of the data was done in the laboratory reference system. The average values of the kinetic energy and angle as well as the kinematic two body laws were used to determine the masses and number of particles emitted by the fragments for each atomic number Z . When the full angular correlation was not measured, the first moments of the reduced E_3 and E_4 distributions corresponding to a small window in θ_4 centered around the most probably angle $\bar{\theta}_4$ were used.

The entrance channel kinetic energy is roughly 140 MeV above the Coulomb barrier. This energy appears in the exit channel as kinetic, rotational and excitation energy of the fragments. It is expected that the latter energy is dissipated through evaporation of particles and γ -ray emission. Apart from the particles evaporated by the fragments, it is possible that nucleons may be emitted either by the incoming ion before full dissipation of its kinetic energy by friction forces, or by the composite system before separation of the fragments. Emission of alpha particles in the very early stages of the collision has been invoked to explain the pronounced forward peaking of the angular distribution of these particles in very light systems involving ^{16}O or ^{14}N projectiles [11,12]. On the other hand, although the experimental situation is not clear yet, particle emission in the case of reactions induced by heavier

projectiles like ^{40}Ar seems to be essentially statistical in nature [1,12]. The analysis of the experimental data described in the following sections was performed assuming that all the emitted particles were evaporated by the fragments after break-up of the composite system.

3.4.1. Total number of evaporated nucleons. Charged particle multiplicities at symmetry

On the average, the energy E_i^* of a primary fragment of mass A_i^* after evaporation of $\bar{\nu}_i^T$ nucleons of mean energy $\bar{\eta}_i$ [13] is:

$$\bar{E}_i = E_i^* \left[1 - \frac{\bar{\nu}_i^T}{A_i^*} \left(1 - \frac{\bar{\eta}_i}{E_i^*} \right) \right], \quad (i = 3, 4) \quad (4)$$

The quantity $\bar{E}_i$ denotes the mean energy after evaporation. The above expression is valid only for a large number of events. The second term in the inner brackets represents the recoil corrections, which are small (6%) in our experiment. To first order Eq. 4 can be written as:

$$E_i^* = \bar{E}_i \left(1 + \frac{\bar{\nu}_i^T}{A_i^*} \right), \quad (i = 3, 4).$$

If we define:

$$K_i = \frac{E_1 A_1}{\bar{E}_i} \frac{\sin^2 \theta_j}{\sin^2(\theta_i + \theta_j)} \quad \left\{ \begin{array}{l} i = 3, 4 \\ j = 4, 3 \end{array} \right\}$$

which contains only measured quantities, Eq. 1 to 3 become to first order:

$$A_3^* + \bar{v}_3^T = K_3 \quad ,$$

$$A_4^* + \bar{v}_4^T = K_4 \quad ,$$

$$A_3^* + A_4^* = A_1 + A_2 \quad .$$

This set of equations shows that the total number of evaporated nucleons from the two fragments ($\bar{v}_3^T + \bar{v}_4^T$) can be obtained to first order without any assumptions on A_3^* and A_4^* . This simple analysis was applied to the average values of the energy and angular distributions yielding the values plotted in Fig. 9 as a function of the Z of the light fragment measured in the E - ΔE telescope. The quantity $\bar{v}_3^T + \bar{v}_4^T$ appears to be essentially constant throughout the Z range of this experiment. If all the energy above the Coulomb barrier (140 MeV) goes into excitation energy of the two binary fragments, the total average number of emitted nucleons can be estimated. From the average binding energy of a nucleon (9 MeV) and a nuclear temperature of the fragments of 2 MeV at the middle of the cascade we obtain $\bar{v}_3^T + \bar{v}_4^T = 11$ nucleons in fair agreement with the above analysis of the experimental data.

Since atomic numbers were resolved up to $Z = 32$, data are available for nearly symmetric decay. Near symmetry it is reasonable

to assume that the relative loss of mass $\frac{\bar{v}^T}{A^*}$ is the same for both fragments. With this assumption and Eq. 1 to 4, the masses of both

fragments $A_{3,4}^*$ prior to particle evaporation and the total number of evaporated nucleons $\bar{v}_{3,4}^T$ can be calculated for each fragment using the experimental data. The results of these calculations are shown in Fig. 10a. It is interesting to notice that a sizable discontinuity is visible in the masses at symmetry. Since consistent agreement was obtained for the elastic scattering data, it appears that the systematic shift observed between the masses of the light and the heavy fragments is not due to experimental difficulties, like an error in the energy calibration and/or angles. It is more likely the indication of charged particle emission from the fragments or by the composite system before break up. Since charged particle emission should be the same for both fragments at symmetry, the number of evaporated charges per fragment is given by the downward and upward shift in Z that must be applied to the two branches to make them overlap. This shift is 1.3 charge units per fragment. In Fig. 10b such a shift has been applied, thus generating a continuous curve. Since projectile and target are neutron rich, the fragments are expected to be also neutron rich and to evaporate mainly neutrons. But the nuclear temperature as well as the angular momentum is fairly high, and the branching ratio for alpha or proton emission may not be negligible. Evaporation calculations described later predict an average of 1.28 evaporated charges at symmetry, in excellent agreement with our data. Evaporation of charged particles was also observed in the symmetric system $\text{Ca} + \text{Ca}$ by Colombani, et al. [14]. They found a charge loss ($\Delta Z = 2$) higher than

that of the present neutron rich system Ar + Ag. In the Ca + Ca case, however, enhanced evaporation of charged particles is expected due to the smaller Coulomb barrier.

3.4.2. Q-Value Analysis

In the preceding analysis it was assumed that the ratio v/A^* was the same for both fragments for symmetric division. While this assumption of thermal equilibration for the fragments is plausible, it has not yet been demonstrated to hold for DIC. One can avoid making this hypothesis by invoking conservation of energy, and by doing so determine the extent to which thermal equilibrium is achieved in the intermediate complex.

After scission and before evaporation, the conservation of energy in the lab system can be expressed as:

$$E_1 + B(A_1, Z_1) + B(A_2, Z_2) = E_3^* + E_4^* + B(A_3^*, Z_3^*) + B(A_4^*, Z_4^*) + E^T,$$

where $B(A, Z)$ is the binding energy of a nucleus with mass A and atomic number Z and E^T is the total excitation energy of the fragments. (Since the target is almost an equal mixture of ^{107}Ag and ^{109}Ag , the binding energy $B(A_2, Z_2)$ was taken as the average of those of the two isotopes.) Implicit in this equation is the assumption that the decay is binary and that no particle emission occurs before scission. After scission the excitation energy is carried off via particle emission and γ -decay. Restricting the particle decay modes to n , p and α emission, one can write

$$E^T = E_n^T + E_p^T + E_\alpha^T + E_\gamma^T ,$$

where E_n^T , for example, denotes the total excitation energy removed through the emission of neutrons. The quantity E_n^T is given by the sum of two terms (one for each fragment) of the form:

$$E_n^j = \sum_{i=0}^{v_j^n-1} \left[B_n(A_j^* - i, Z_j^*) + \eta_j^{i+1} \right] , \quad (j=3,4) ,$$

where $B_n(A,Z)$ is the neutron binding energy and η_j^{i+1} is the $(i+1)$ th average neutron kinetic energy. The neutron energy spectra are expected to be similar to those observed in compound nucleus decay or in fission, which is quasi-Maxwellian. The corresponding mean kinetic energy is $\bar{\eta} = 2T$. In what follows the mean temperature T was estimated from the mean excitation energy at the middle of the cascade, using a level density parameter of $A/8$. Since the excitation energy is high, shell effects have been neglected.

Similar expressions can be written for E_p and E_α . For charged particles the mean kinetic energies were calculated by adding the Coulomb energy to the Maxwellian distribution (using $r_0 = 1.5$ fm and an effective barrier height $B_{\text{eff}} = .8B_c$ [15]). The partition of the average evaporated charge between α particles and proton was taken from evaporation calculations which are described later. The quantity $\bar{v}^T$ appearing in Eq. 4 was modified to incorporate the effect of charged particle emission; that is,

$$\bar{v}_j^T = \bar{v}_j^n + \bar{v}_j^p + 4\bar{v}_j^\alpha, \quad (j = 3, 4) \quad .$$

The total γ -ray energy, E_γ , can be estimated from the "sticking" model, in which it is assumed that E_γ is the sum of the individual rotational energies of two spherical fragments rotating rigidly. The sticking hypothesis is supported by recent γ -multiplicity experiments on the similar system $^{nat}\text{Ag} + 175 \text{ MeV } ^{20}\text{Ne}$ [16]. In addition, a fraction (2/3) of the binding energy of the last neutron was added to the sticking model prediction to account for the variation in excitation energy at the end of the evaporation cascade.

3.4.3. Iterative Calculations

From the considerations of the previous sections, it is now possible to calculate the quantities A_3^* , A_4^* , $\bar{v}_3^T$, $\bar{v}_4^T$, E_3^* and E_4^* from the experimentally measured values E_3 , E_4 , θ_3 , θ_4 and Z_3 , the known quantities A_1 , Z_1 , A_2 , Z_2 and E_1 and the calculated values $\bar{v}_3^p$, $\bar{v}_4^p$, $\bar{v}_4^\alpha$ (which reproduced the experimental ΔZ at symmetry). This is accomplished via the simultaneous solution of the following equations: conservation of momentum of the primary fragments,

$$E_j^* A_j^* = \frac{E_1 A_1 \sin^2 \theta_i}{\sin^2(\theta_i + \theta_j)}, \quad \left\{ \begin{array}{l} i = 3, 4 \\ j = 4, 3 \end{array} \right\}; \quad (5)$$

conservation of energy and momentum for the evaporating fragments
(neglecting recoil effects),

$$E_j^* = \bar{E}_j (1 + \bar{v}_j^T / A_j) \quad , \quad (j = 3, 4) \quad ; \quad (6)$$

conservation of total energy,

$$\begin{aligned} E_1 + B(A_1, Z_1) + B(A_2, Z_2) = E_3^* + E_4^* + B(A_3^*, Z_3^*) \\ + B(A_4^*, Z_4^*) + E_n^T + E_\alpha^T + E_P^T + E_Y^T \quad ; \end{aligned} \quad (7)$$

conservation of charge,

$$\begin{aligned} Z_1 + Z_2 = Z_3^* + Z_4^* = Z_3 + Z_4 + \bar{v}_3^P + \bar{v}_4^P \\ + 2\bar{v}_3^\alpha + 2\bar{v}_4^\alpha \quad ; \end{aligned} \quad (8)$$

and conservation of mass,

$$A_1 + A_2 = A_3^* + A_4^* = A_3 + A_4 + \bar{v}_3^T + \bar{v}_4^T \quad . \quad (9)$$

Since the above system of equations is highly nonlinear, an iterative procedure was developed to obtain a solution. (Similar calculations have been performed in fission studies [17]). The following outlines the procedure:

Step 1. Reasonable guesses are made for all the variables.

Step 2. The ratio $\bar{v}_3^T / \bar{v}_4^T$ is estimated from Eqs. (5) and (6).

Step 3. With this ratio and the calculated values of

$\bar{v}_3^P$, $\bar{v}_4^P$, $\bar{v}_3^\alpha$ and $\bar{v}_4^\alpha$, Eq. (7) is used to determine

$\bar{v}_3^T$ and $\bar{v}_4^T$.

Step 4. The excitation energies of the fragments, the corresponding nuclear temperatures and the quantities

E_n^T , E_p^T , E_α^T and E_γ^T are then calculated.

Step 5. Eqs. (6) are used to calculate the ratio A_3^*/A_4^* .

Step 6. Mass conservation (Eq. (9)) is used to calculate

A_3^* and A_4^* .

Step 7. The quantities E_3^* and E_4^* are then determined from

$\bar{v}_3^T$, $\bar{v}_4^T$, A_3^* and A_4^* using Eqs. (5) and (6).

Step 8. If convergence (requiring the mass difference between two successive iterations to be less than .01 mass unit) was not achieved, the process was repeated starting with Step 2.

The calculations generally converge fairly rapidly (3-4 iterations).

The results of these calculations are given in Fig. 11 which shows the masses prior to evaporation and the number of evaporated neutrons as a function of Z_3^* (before evaporation of charge). Around symmetry, the agreement with the simple analysis done before (Fig. 10b) is good. The upper solid line represents the masses calculated by assuming charge equilibrium between two liquid drops in contact [4]. The good agreement with this model confirms the conclusions of B. Gatty et al. [4] for the lighter Ar + Ni system, namely that charge equilibrium at fixed mass asymmetry is indeed achieved in deep inelastic collisions for the part of the angular distribution beyond the grazing angle. The lower dashed line represents the calculated values of $\bar{v}^n$ from the code EVA described in the next

section. The good agreement with the experimental values suggests that thermal equilibrium is achieved between the fragments as was postulated when establishing the input parameters of the evaporation calculations.

3.4.4 Evaporation calculations

In order to estimate the number of charged particles emitted by the fragments, evaporation calculations were performed with the code EVA-II developed by Dostrovsky et al. [18]. This code was written for the analysis of compound nucleus reactions leading to masses and excitation energies similar to those of the deep inelastic fragments from the reaction 340 MeV Ar + Ag but with smaller angular momentum for the compound nucleus. It was assumed that the average mass corresponding to a given Z^* was given by the charge equilibrium model [4]. The total excitation energy calculated from the kinetic energy balance was assumed to be shared by the two fragments in proportion to their mass. The level density parameter and the radius parameter were taken as $\frac{A}{10}$ and 1.5 fm as suggested by the authors of the code as being the most suitable for this mass and energy domain. Angular momentum effects are not taken into account in this code nor any competition between particle and gamma-ray emission.

At 70° in c.m. one would expect that the intermediate complex has met the sticking condition leading to rigid rotation of the system. If this condition is achieved, most of the angular momentum goes into relative motion so that the intrinsic angular momenta of the fragments should be low except for extreme asymmetries; however, the ratio $\frac{\Gamma_\alpha}{\Gamma_n}$ is sensitive to angular momentum as shown by various authors (e.g. [19]).

Using the simple expression given by Williams et al. [19] the spin dependent ratio $\frac{\Gamma_{\alpha}(E,J)}{\Gamma_n}$ can be expressed as

$$\frac{\Gamma_{\alpha}}{\Gamma_n}(E,J) = \frac{\Gamma_{\alpha}}{\Gamma_n}(E, J=0) \exp \left[\frac{(m_{\alpha} - m_n)r^2}{\mathcal{I}} \times \frac{E_{\text{rot}}}{T} \right],$$

if the fragment rotational energy E_{rot} is small compared to its excitation energy. To obtain this expression it was assumed that the interaction radius r and the nuclear temperature T were the same for neutrons and α particles of mass m_n and m_{α} , respectively. The quantity $\mathcal{I}$ is the moment of inertia of the fragment. If the rigid moment of inertia is used, this expression reduces to the simple relation

$$\frac{\Gamma_{\alpha}}{\Gamma_n}(E,J) = \frac{\Gamma_{\alpha}}{\Gamma_n}(E, J=0) \exp \left(\frac{15}{2} \frac{E_{\text{rot}}}{AT} \right). \quad (10)$$

For light systems like Ar + Ag the fusion cross section is rather large, and the angular momenta involved in DIC are not expected to be very different from the maximum angular momentum ℓ_{max} . Figure 12 shows the sticking model prediction for the rotational energy E_{rot} as a function of the mass of the fragment with an entrance channel angular momentum $L = 100$. It is interesting to notice that for the light fragment E_{rot} is almost linear with A and yields a constant spin effect term in Eq. (10) independent of the size of the fragment. This term has been implemented in the code. Table 1 summarizes the result of the evaporation calculations.

4. WIDTHS OF THE ANGULAR CORRELATIONS

As a consequence of the binary decay of the composite system, the heavy fragment direction should be in the plane of the reaction, defined by the beam direction and by the position of the light fragment detector. Another characteristic of binary fragmentation concerns the angle θ_4 of the heavy fragment which should be unambiguously defined when the energy E_3^* and angle θ_3 of the light fragment are fixed (Eq. 1).

Emission of particles prior to or after the break-up of the system perturbs the direction of the velocity of the fragments, and leads to a spreading of the heavy fragment direction in the plane as well as out of the plane of the reaction. The widths of the in-plane and out-of-plane angular distributions are directly related to the nature and energy of the evaporated particles. Sikkeland et al. [20] has calculated the variance of the angular distribution for fission fragments expected from recoil effects due to evaporation of prompt neutrons. The following expression, in which $\bar{\nu}$ is the average multiplicity and $\bar{\eta}$ is the average kinetic energy (in the c.m. system of the recoiling fragment) of the neutrons, relies on the isotropy of the angular distribution of the neutrons evaporated from a fragment with kinetic energy E^* and mass number A^* :

$$\sigma_{\theta}^2 = \frac{1}{2} \frac{\bar{\nu}\bar{\eta}}{A^*E^*} \quad , \quad (11)$$

where θ is the angle which measures the deflection from the initial direction. Of course, in the present experiment both light and heavy

fragment evaporation contribute (in an uncorrelated way) to the observed θ_4 angular distribution. While the heavy fragment contribution can be directly calculated from Eq. (11), the combined effect of light and heavy fragment evaporation must be calculated from kinematics. The following first order expression contains both contributions:

$$\sigma_{\theta}^2 = \frac{1}{2} \frac{\bar{\eta}_3 \bar{v}_3 + \bar{\eta}_4 \bar{v}_4}{A_4^* E_4^*} .$$

This equation reduces to

$$\sigma_{\theta}^2 = T \frac{\bar{v}_3 + \bar{v}_4}{A_4^* E_4^*} , \quad (12)$$

if we assume that the nuclear temperatures of the fragments are the same as indicated by the iterative calculations described in a previous section ($T_3 = T_4 = T$). This expression applies to both the in-plane and to the out-of-plane distributions if the energies of the fragments before evaporation are restricted to a narrow band around average values E_3^* and E_4^* . While the actual energy spread (due to the dynamics of the collision between the two ions) does not affect the out-of-plane width to first order, it induces a kinematic broadening of the in-plane θ_4 distribution (see Eq. 1).

4.1 Out of plane widths

Figure 13 gives the experimental out-of-plane angular distributions of the heavy partner for representative atomic numbers. These distributions are peaked at $\phi_4 = 0^\circ$ and drop rapidly on both sides

as expected from binary division followed by evaporation. From the total mass loss determined in the iterative calculations it is possible, using Eq. (12) to estimate the variance of the out-of-plane distribution for each Z . These calculations are compared (Fig. 14a) to the experimental values for three cases:

- i) Only neutrons are emitted (dashed curve).
- ii) Neutrons, protons, and alpha particles are emitted (solid curve).
- iii) All charged particles emitted at symmetry are alpha particles (solid triangle).

Comparison with experimental data seems to indicate that alpha particle emission is not the dominant process at symmetry, and show that the results are consistent with the iterative calculations.

4.2. In-plane widths

The standard deviations of the experimental in-plane correlations (see Fig. 6) are plotted in Fig. 14b. Because of the limited angular range of the PSD, accurate determination of the second moment of these distributions was not possible above $Z_3 = 26$.

These experimental values are compared to the standard deviations calculated, as described in the previous paragraph, from particle multiplicities obtained in the iterative calculation (including protons and alpha particles). The kinematic contribution was added to these calculated values. This contribution is small ($\sigma_{\theta 4}^2 = 4.8 \text{ deg}^2$ for $Z_3 = 10$) for very asymmetric division because of low values of the product $E_3^* M_3^*$, but increases substantially when the division becomes more symmetric ($\sigma_{\theta 4}^2 = 13 \text{ deg}^2$ for $Z_3 = 26$).

Although the experimental errors are rather large, the particle multiplicities obtained in the iterative calculations seem to be in agreement with the in-plane and out-of-plane widths of the angular correlations. Another point to mention is that since the out-of-plane and the in-plane widths are both reproduced, the alignment of the angular momentum does not seem to favor substantially the in-plane emission of particles. This same conclusion was obtained by Gelbke et al. [21] in a two fragment coincidence experiment on the lighter system $^{32}\text{S} + ^{50}\text{Ti}$.

5. CROSS SECTIONS

The ultimate proof of the two body character of a reaction is obtained by comparing singles and coincidence cross sections. If a sizable part of the cross section was due to nonbinary events, corresponding to either a ternary splitting of the composite system or fission of the heavy partner following DIC, the concept of reaction plane would vanish and the angular correlation of two of the ternary fragments would be extremely broad in the CM system. This would scatter considerably the yield of coincidence events in space, leading to a small flat background under the peaked angular distribution of binary events.

The differential laboratory cross section $\frac{d\sigma}{d\Omega}$ corresponding to various Z values of the light fragment which were deduced from the in-plane experiment are plotted in Fig. 15 with and without the coincidence requirement. The singles cross sections are in good agreement with a previous experiment on the same system [9]. The coincidence cross section was obtained after correcting the data for the detection efficiency of the PSD. This efficiency is small because the out-of-plane acceptance angle

of the PSD (2.6°) is much smaller than the width of the angular distribution (FWHM = 10°) of the heavy fragment (Fig. 13). To perform that correction it was assumed that the shape of these distributions is well represented by a Gaussian.

Singles and coincidence cross sections appear to be equal for a very broad range of Z. Slight differences at the edges of the Z distribution are explained by the limited angular range of the PSD, which prevents one from measuring the full angular correlation (Fig. 6). This equality of cross sections strongly confirms the two body character of the reaction even for extreme asymmetries, and tends to indicate that, despite the very high excitation energy, fission of the heavy fragment following DIC is unlikely to occur in such light systems.

CONCLUSION

The coincidence study of the system $^{nat}\text{Ag} + 340 \text{ MeV } ^{40}\text{Ar}$ has provided valuable insight into the reaction mechanism and the time scales of various relaxation phenomena in DIC. From the simultaneous measurement of the energies and angles of both primary fragments as well as the Z of one fragment, it has been possible to confirm the binary nature of the reaction and to directly measure the total charge emitted in the symmetric decay mode. Guided by two body kinematics, an iterative procedure has been described which allows one to calculate the masses of the fragments before as well as after particle emission. The validity of this procedure is supported by the agreement between the calculated and measured widths of the in-plane and out-of-plane correlations. The results of iterative calculations are in agreement with evaporation calculations.

Our finding may be summarized as follows:

- 1) the entrance channel kinetic energy (in excess of the Coulomb repulsion energy) is thermalized during the interaction, resulting in two highly excited fragments which decay via the emission of light particles and γ -rays;
- 2) equilibrium of the excitation energy is achieved between the fragments at fixed mass asymmetry;
- 3) the charge-to-mass ratio of the fragments is equilibrated at fixed mass asymmetry.

With regard to point 3) it should be pointed out that, while similar conclusions have been reached by other authors who have measured both the Z and A of DI fragments, the pre-evaporation charge and mass are not directly accessible to such single particle inclusive experiments. Since a knowledge of Z^* and A^* is necessary to test charge equilibration, the ultimate confirmation can only be achieved in coincidence measurements. Future experiments are planned to extend the measurements into the quasi-elastic region.

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TABLE 1

Evaporation calculations with the EVA II code [18]. For each atomic number Z_3^* the mass number A_3^* was chosen according to the charge equilibrium model of two touching liquid drop [4]. The total excitation energy calculated from the energy balance was assumed to be shared by the fragments in proportion to their mass ($E_3^{\text{ex}}/A_3^* = E_4^{\text{ex}}/A_4^*$).

Light Fragment						Heavy Fragment			
Z_3^*	A_3^*	$E_3^{\text{ex}} \text{ (MeV)}$	$\bar{\nu}_3^n$	$\bar{\nu}_3^p$	$\bar{\nu}_3^\alpha$	$E_4^{\text{ex}} \text{ (MeV)}$	$\bar{\nu}_4^n$	$\bar{\nu}_4^p$	$\bar{\nu}_4^\alpha$
10	22	20.4	1.0	0.	.03	116.9	6.7	.79	.27
11	24	21.9	1.0	.05	.21	111.9	6.4	.81	.25
12	27	23.2	1.5	.02	.01	106.5	6.3	.82	.23
13	29	26.3	1.9	.02	.01	109.2	6.4	.75	.18
14	31	29.0	1.8	.09	0.3	109.2	6.5	.80	.16
15	33	29.2	1.8	.10	.04	100.6	6.4	.43	.11
16	36	31.3	1.9	.10	.08	98.9	6.2	.60	.16
17	38	32.4	2.0	.13	.17	94.1	6.1	.36	.16
18	40	35.8	2.0	.13	.14	96.0	6.2	.40	.20
19	43	39.5	2.6	.22	.12	98.0	6.3	.32	.21
20	45	40.5	2.3	.19	.13	93.3	5.8	.60	.09
21	47	41.6	2.6	.19	.08	89.0	5.9	.36	.16
22	49	48.2	2.5	.39	.04	96.0	5.7	.59	.21
23	52	50.8	2.9	.41	.07	94.0	5.5	.58	.23
24	54	55.3	3.0	.38	.10	96.0	5.4	.77	.20
25	56	58.6	3.3	.44	.13	95.1	5.1	.91	.13
26	59	62.3	3.9	.23	.12	94.6	4.3	1.02	.08
27	61	66.0	3.9	.47	.09	93.9	5.0	.83	.12
28	63	68.6	4.0	.37	.17	91.5	4.9	.84	.15
29	66	69.3	4.2	.44	.12	86.1	4.8	.60	.16
30	68	71.0	4.0	.48	.36	83.3	4.7	.64	.14
31	71	73.4	4.1	.53	.36	80.7	4.7	.48	.21
32	79	76.7	4.3	.61	.36	79.2	4.1	.74	.24

FIGURE CAPTIONS

- Fig. 1 Chamber configuration. Subscripts 3 and 4 refer to light and heavy fragment respectively.
- Fig. 2 Pulse height defect for gold, silver, and copper ions in the position-sensitive detector as a function of the ion energy.
- Fig. 3 Same as Fig. 2. LSS units are used for the energy and the pulse height defect.
- Fig. 4 Comparison of experimental and calculated energies of the scattered projectile and target from elastic scattering of 163 MeV ^{40}Ar on Au(x), Ag (●), and Cu(o). The solid lines represent the calculated values.
- Fig. 5 Kinetic energy distributions of the light fragment. The open points refer to singles data and the closed points (with error bars) to coincidence data. The area of the coincidence distribution was normalized to the singles data.
- Fig. 6 In-plane angular distribution of the heavy fragment in coincidence with light fragments for selected cases. The arrows represent the kinematic angle predicted from Coulomb repulsion of two spheres (plus 2 fm) and a radius parameter $r_0 = 1.23$.
- Fig. 7 a) Correlated distribution E_3, θ_4 corresponding to $Z_3 = 20$. The solid line represents the two body kinematical prediction for the variation of the energy E_3^* with the angle θ_4 using the preevaporation mass $M_3^* = Z_3 \left(\frac{M}{Z}\right)_{\text{c.n.}}$. b) Correlated distribution E_4, θ_4 . The solid line represents the same prediction as in Fig. 7a for the energy E_4^* .

Fig. 8 Same events as in bottom of Fig. 7 projected on the E_4 axis and separated into two populations corresponding respectively to $\theta_4 < 46.5^\circ$ (closed points) and $\theta_4 > 46.5^\circ$ (open points).

Fig. 9 Total number of nucleons evaporated by the fragments.

Fig. 10 a) Masses before evaporation and number of nucleons evaporated for fragments close to symmetry plotted versus the Z after evaporation.

b) Masses before evaporation and number of neutrons evaporated plotted versus the Z before evaporation.

The symbols (●) and (■) refer to the light and heavy fragments respectively.

Fig. 11 Masses prior to evaporation and number of evaporated neutrons as a function of the Z before evaporation from the fragments. Symbols (Δ) and (●) refer to light and heavy fragments respectively. The upper solid line represents the masses calculated with the charge equilibrium model of ref. 4.

The lower dashed line represents the number of neutrons evaporated as predicted by the code EVA II [18] assuming that the excitation energy is shared by the fragments in proportion to their mass.

Fig. 12 Sticking model prediction of the rotational energy E_{rot} of the individual fragments as a function of their mass.

Fig. 13 Out-of-plane distributions for various Z values.

Fig. 14 a) Standard deviations of the out-of-plane (laboratory frame of reference) angular distributions of the heavy fragments in coincidence with light fragments of Z ranging from 10 to 32. Experimental points are compared to calculated values from eq. 12 in three cases.

- i) all evaporated particles are neutrons (dashed curve)
- ii) neutrons, protons, and alpha particles are emitted (solid curve)
- iii) all charged particles evaporated at symmetry are alpha particles (Δ).

b) Same as Fig. 14a for the in-plane angular distribution of the heavy fragment. The dashed curve refers to case ii). Kinematical broadening has been included.

Fig. 15 Comparison of cross section obtained with (triangles with error bars) and without (solid curve) coincidence requirement. The dashed curve at $Z = 18$ reflects a large uncertainty in the singles cross section.

Fig. 1

XBL 766-8211

Fig. 2

XBL 766-8212

Fig. 3

XBL 766-8213

Fig. 4

$$^{nat}_{47}\text{Ag} + 340 \text{ MeV } ^{40}_{18}\text{Ar}$$
$${}^{40}_{18}\text{Ar}$$

- Coincidences
 - Singles

- Singles

XBL 779 - 2340

Fig. 5

XBL779-2339

Fig. 6

$$Z_3 = 20, \theta_3 = 42^\circ$$

XBL 779-2343

Fig. 7

XBL779-2342

Fig. 8

XBL 778-1731

Fig. 9

XBL766-8209

Fig. 10

Fig. 11

XBL 778-2563

XBL 778-2890

Fig. 12

$\text{natAg} + 340 \text{ MeV } ^{40}\text{Ar}$ out - of - plane correlations

XBL779 -2341

Fig. 13

Fig. 14

XBL 778-2624

XBL 778-2889

Fig. 15

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