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Abstract

Heavy fragments of mass approximately 160u are observed in the reaction ^{40}Ar (44 and 77 A.MeV) + ^{232}Th. The data indicates that they are products of high excitation following deep inelastic processes. At 27 A.MeV the yield of heavy fragments is small. Bolzmann-Nordheim-Vlasov calculations give a good description.

It has been shown that for reactions induced by heavy projectiles on fissile targets the yield of events corresponding to high linear momentum transfer, LMT, diminishes with increasing bombarding energy [1-3]. Several explanations have been put forward: The corresponding fission cross-section could be channelled into many body final states through dynamic or statistical processes. Alternatively, a possibility is that the rapid and prolific emission of light particles and intermediate mass fragment, IMF, could leave the residual complex with an effectively high fission barrier. Therefore fission will be inhibited at the profit of evaporation residue formation. Thus the motivations of the present work was to establish the existence of heavy fragments resulting from processes involving high recoil velocities and energy deposit and to examine the reaction mechanism that produces them.

Experiment

GANIL provided the ^{40}Ar beams at 27, 44 and 77 A.MeV. The target was metallic ^{232}Th of thickness 0.7 mg/cm². Thorium has the advantage of having a low fission barrier and therefore it allows a discrimination between the target recoils and evaporation residues through the measurement of the mass spectra. The experimental set-up is shown in fig. 1, where the z-axis corresponds to the beam direction. The objective behind the set-up is to detect the heavy fragments at forward angles via silicon counters (Si). Also, to filter events

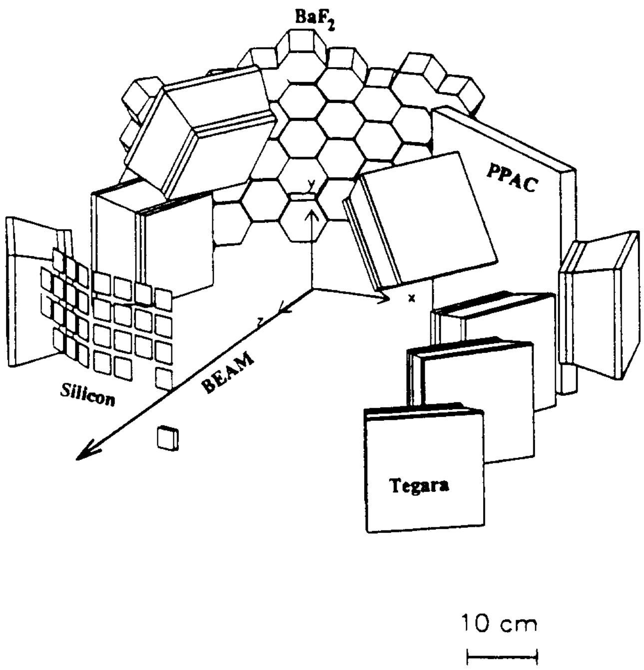

Fig. 1 Experimental set-up

with high excitation energy, data was collected in coincidence with light charged particles, LCP, at back angles and intermediate mass fragments, IMF, over a large range of angles. In addition, to discriminate against asymmetric fission events in the Si, a parallel plate ($30\times30cm^2$) avalanche counter was placed at 30cm from the target at a mean angle of 145° relative to the beam. The timing reference for all detectors was taken relative to the RF of the cyclotron. The time resolution between the RF and the Si for elastic scattering was typically 0.7ns.

The detection of heavy fragments, HF, and fission fragments, FF, was achieved by 32 high electric field silicon, Si, diodes (3×3 cm^2), 140μm thick, located at 40cm from the target and spanned an in-plane angular range, of -8.5° to -45°. Calibrations for these detectors were done using a ^{252}Cf source on a thin backing, the beam and precision pulser. Energy [4] and time [5] defect corrections were employed to obtain the mass and velocity calibration. IMFs ($3\leq Z\leq 16$) were detected in 8 ionisation chambers, TEGARA [6], each consisting of a split anode coupled to four $5\times5cm^2$ silicon diodes of thickness 500μm. CF_4 gas with a depth of 5.4cm and pressure of 30 torrs was used. These detectors were located at -120, -110, 35, 48, 60, 65 and 100° to the beam direction. As shown in fig. 1 two of these chambers were placed out-of-plane. The energy and identification measurements of the LCP (p, d, t, ^{3}He and alphas) were obtained with the honey-comb array (fig. 1) containing 36 BaF_2. The crystals were 5cm thick with a cross-sectional area of 25cm^2 [7] and the whole arrangement covered an in-plane angular range between -130 and -170°

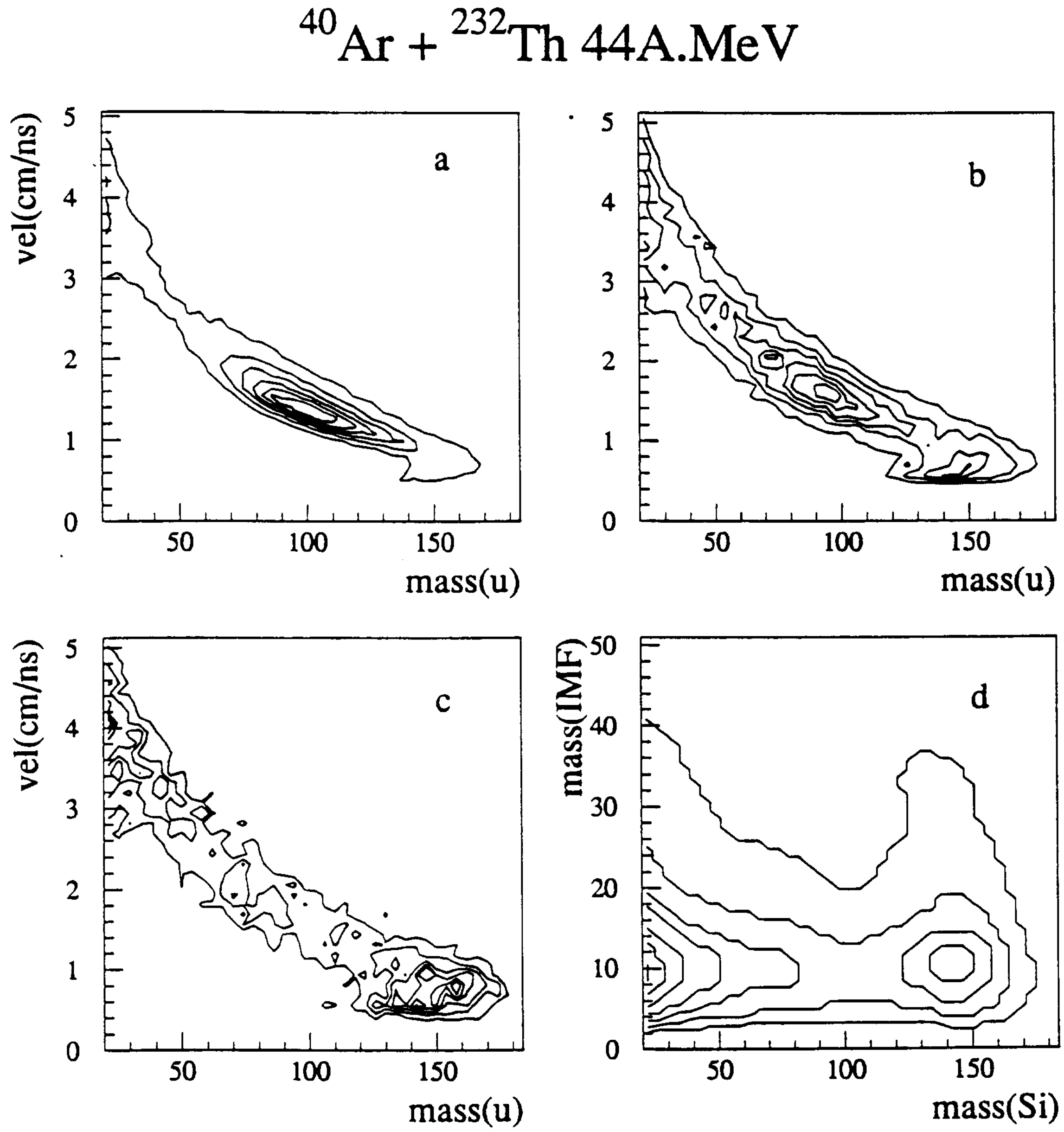

Fig. 2 a) Mass-Velocity in singles mode.
b) as in a) in coincidence with LCP.
c) Mass-Velocity, 8 to 25° in coincidence with LCP and IMF
d) Mass(Si)-Mass(IMF) as for c)

The singles data from the Si counters at 44 A.Mev show a strong FF contribution in the velocity versus mass plot (fig. 2a) with no apparent HF contribution. But, introducing a coincidence requirement of at least one LCP (fig. 2b) gives rise to two components at approximately 95 and 160 units of mass. The lower mass peak is attributed to fission. The HF contribution at 160u, corresponds to a distribution limited by the velocity threshold of 0.5cm/ns and has a mean velocity of about 0.8cm/ns. Further, coincidence spectra at large angles (45°) show a strong decrease in the HF yield. Similar results are obtained at 77 A.MeV with the HF mass peak being shifted to lower values. On the other hand, at 27 A.MeV there is only a weak presence of HF events. A comparison between the mean mass for the same recoil velocity shows that for HF the mass of 160u is approximately 30u smaller then for FF correlation data which could suggest a significantly larger deposit of energy for HF events.

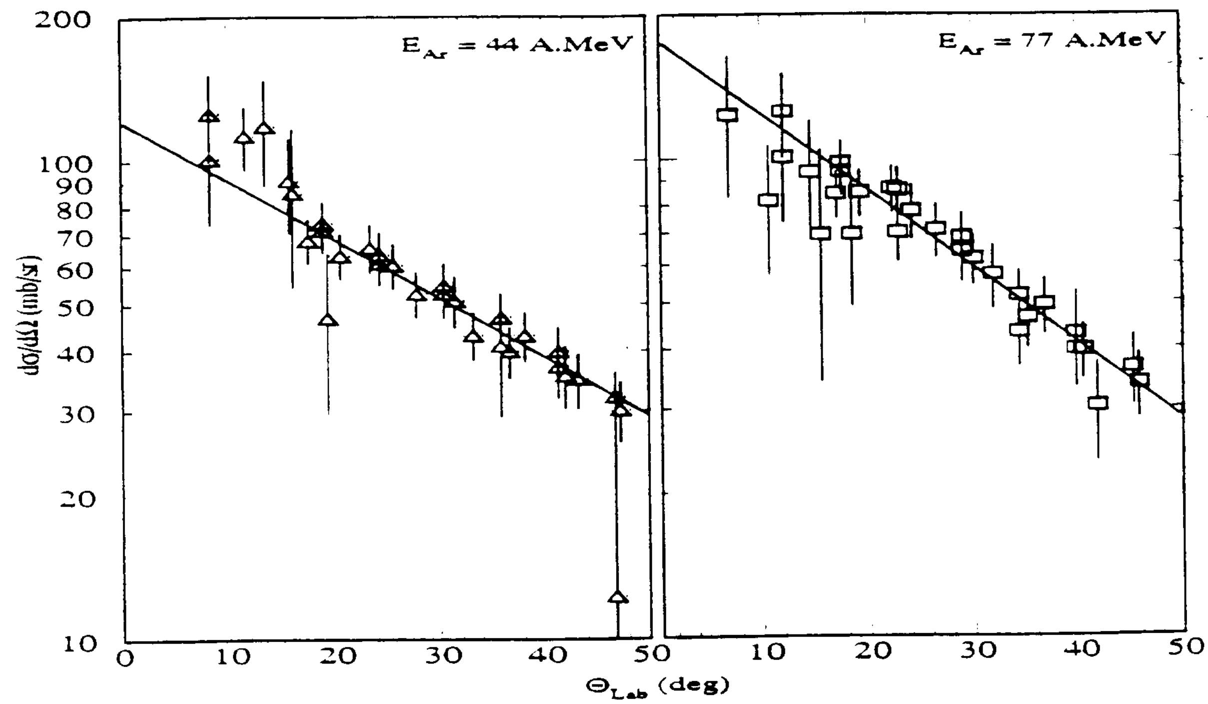

Fig. 3 Angular Distributions for heavy fragments.

It is important to note that LCP requirement introduces an enhancement also for masses of about ≈40u (see also ref. [8]) This suggests that the events which are being labelled HF could arise from strongly asymmetric fission. However the mass and velocity spectra for the forward Si in coincidence with the PPAC and LCP show no mass peak contribution at ≈ 160u. A simulation using the experimental geometry, shows that this result eliminates normal asymmetric fission as a HF production process.

To evaluate the cross-sections from the singles measurement a deconvolution procedure was adopted to separate FF from HF in the velocity spectra. For the HF a Gaussian tail was assumed , with characteristics extracted from the coincidence LCP-Si data. The fission component was fitted by a Gaussian as suggested by the coincidence PPAC-Si projected velocity spectra for fission. Using a χ^2 minimisation procedure and integration over velocity gave the angular distributions in fig. 3. As expected from the coincidence data the distributions show a steep fall off with angle. To extract HF cross-sections the angular distributions were fitted with an exponential function and extrapolated to the full angular range. The integrated differential cross-section are given in table 1 and show that within the given velocity threshold, they are relatively constant with incident energy. Comparing these values with those of Schwinn et al. [3] shows a good agreement at 44 A.MeV but a large variance at 77 A.MeV.

HF mean velocity and mass values over the measured distributions were extracted from the Si-LCP correlations and are summarised in table 1. At 44 A.MeV the values are consistent with those of Utley et al. [8]. The LCP energy spectra for the events in coincidence with the HF were transformed in the rest frame of the HF and fitted using a Maxwell-Bolzmann function. The α particle spectra are well fitted over the full dynamic range with apparent temperatures given in table 1 and Coulomb barriers corresponding to mother nuclei of charge 75 and mass 190 (N/Z was chosen to be in the valley of stability). For the protons the fits show an enhancement beyond 30 MeV, reminiscent of pre-equilibrium forward angle data [9]. To obtained the mean LCP multiplicities the relative yields as a function of the LCP multiplicities from the HF-LCP coincidences were compared with a simulation. The simulation took into account the experimental geometry (GEANT 3.15) and fitted the HF and LCP momentum and mass distributions. The LCPs were assumed to be emitted isotropic in the frame of the HF. The quoted multiplicities are minimal values because no background subtraction for, FF-LCP was performed.

Table 1
Experimental results

Beam Energy	44 A.MeV	77 A.MeV
σ(>0.5cm/ns)	290 mb	250mb
<M>	160 $\pm$ 10 u	145 $\pm$ 10 u
<V>	0.9 $\pm$ 0.1 cm/ns	0.84 $\pm$ 0.1 cm/ns
M_{LCP}	> 6	>7.5
Temp. (α-HF)	5.1 MeV	5.0 MeV

In fig. 2c the mass-velocity plot for the Si-LCP-IMF coincidences is given along with the corresponding mass(Si) vs. mass(IMF), fig. 2d. The IMFs in these figures include all TEGARA angles with the exception at 110° and the mass for the IMFs was assumed to be twice that of the charge. The more striking feature is that the correlations are indeed quite strong for the HF. A kinematic reconstruction between the IMFs and the HF shows a strong LMT imbalance of, 40-50% relative to full LMT. Further, the angular correlations and TKE characteristics are reminiscent of deep inelastic collisions [9], where beyond 48°, the IMF's have a completely relaxed energy distribution. To obtain an estimate of the 'evaporative' IMF multiplicity the IMF-HF cross-section was assumed to be isotropic and with experimental values from back angle correlations. The extracted value is approximately one. Further, by integrating the small angle correlations up to 48° a rough estimate of 1.8 IMFs (multiplicity) is obtained.

BNV calculations.

Kinetic equations, like the Bolzmann-Nordheim-Vlasov, BNV, equation have been widely used to simulate the evolution of heavy ion collisions in the intermediate energy range. The dynamical description of the collision mechanism, which takes into account entrance channel effects and non-equilibrium features, allows to deal with a variety of processes, ranging from complete or incomplete fusion to deep-inelastic reactions [10].

For the present system at 44 A.MeV, the most important properties (mass A, velocity V_{lab}, excitation energy E*, intrinsic angular momentum J) of the primary fragments formed through the dynamics are shown in table 2 at a time when pre-equilibrium effects have ceased, for different impact parameters, b. It is to be remarked that the pre-equilibrium particles remove almost half the available energy in the centre of mass and approximately 30 nucleons from the total mass.

At intermediate values of b, for 44 and 77 A.MeV a transition from incomplete fusion to deep inelastic mechanism occurs, characterised by the formation of two intermediate mass fragments, together with a HF. This is in qualitative agreement with the data, however for a closer comparison a study of the decay stage is called for. Work on this is in progress.

Finally it is interesting to note that the pre-equilibrium effects are less important at 27 A.MeV (calculations not given) essentially two fragments are present in the exit channel for intermediate values of b. Consequently for deep inelastic collisions the larger fragment has a large probability to decay by fission.

Table 2
BNV calculations for $^{40}Ar + ^{232}Th$ at 44 A.MeV

b (fm)	A (u)	E* (MeV)	J h	V_{lab} (1/c)
2	242	700	72	0.04
4	245	684	127	0.04
6	5	12	1	0.12
	44	45	27	0.044
	177	178	107	0.03
8	28	28	1	0.12
	14	76	3	0.24
	216	26	65	0.016

Discussion

The results given above permit a description where the HFs emerge from a nuclear complex raised at high excitation energy. The neutron [3,8], LCP and IMF multiplicities support this view. As for the apparent temperatures, they are average values in a long chain of evaporation, nonetheless they are consistent with high temperatures being reached. Also, the tabulated values support a process where at 77A.MeV higher excitation energies are reached. Further, the IMFs at forward angles indicate a deep inelastic mechanism.

The BNV calculations present a consistent picture of the data. At intermediate impact parameters the model forms (i) a highly excited complex (ii) within a deep inelastic characteristic. Also, in addition, (iii) the loss of mass, energy and angular momentum through pre-equilibrium emission and the intermediate mass favours the formation of HFs. The resulting (iv) recoiling velocity and the forward thrust of the resulting complex are in agreement with the data. Finally the calculations show (v) a characteristic change above 27 A.MeV. Namely at 27 A.MeV, the resulting system remains relatively heavy and with high angular momentum for all impact parameters and therefore should not produce HFs. This is compatible with the data.

In conclusion, the data shows that in $^{40}Ar + ^{232}Th$ at 44 and 77 A.MeV, HF are observed and are the products from a nuclear complex at high excitation energy. The cross-sections with the given experimental thresholds are constant with incident energy and are relatively small compared to the missing central collision values [1]. At 27 A.MeV the cross-section for HF is small. BNV calculations are presented and give a good overall qualitative description of the data.

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