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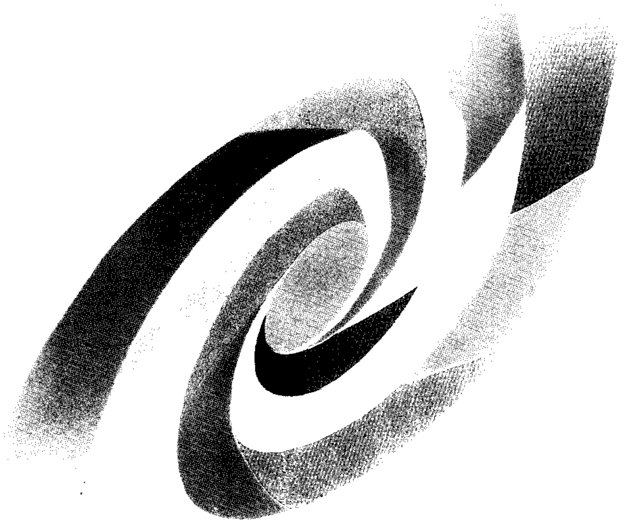

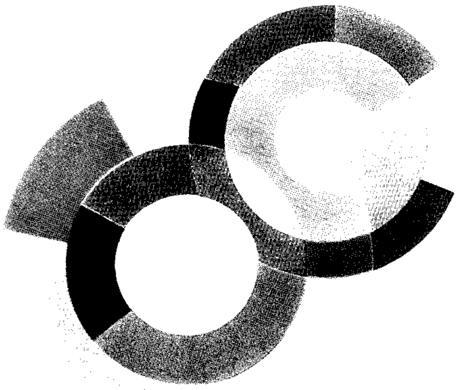

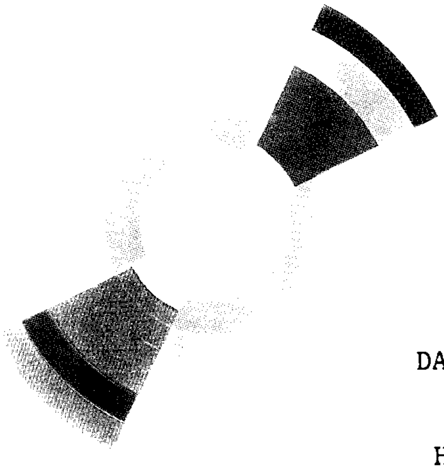

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HEAVY FRAGMENTS IN THE REACTION ^{40}Ar + ^{232}Th AT 27.44 AND 77 A.MeV

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Heavy fragments in the reaction $^{40}Ar+^{232}Th$ at 27, 44 and 77 A.MeV.

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The motivation for the present measurement could be framed within the theoretical work of Bonche et al. [1] who suggest that limits of excitation energy, E^*_{lim}, in nuclei presents a means to establish parameters for the equation of state in nuclear matter. Experimentally, it is well known that collisions between heavy ions allow a deposit of energy in a composite system to cover E^*_{lim}. However, to establish the limits of existence it is necessary to understand the mechanism of the energy transfer and subsequent thermalisation and decay.

In reaction on fissile targets, the measurement of fission angular correlations relate to the Linear Momentum Transfer, LMT, from the projectile to the target. In turn, the LMT is correlated to the energy thermalised in the formed complex [2]. What is interesting with such data is that the cross-section for large LMT decreases strongly with incident energy [3,4] and the question is raised as to whether the missing yield could be related to E^*_{lim}. Leaving apart all feasible dynamic processes, it is possible to explain the observed lack of cross-section through an increase of evaporation residue production. The line of argument being, that the early light charged particles and intermediate mass fragments emission[5] are so prolific that they leave the residual complex with an effectively high fission barrier. Thus, the motivation of this contribution is to study the evaporation residue production process, which in itself might act as a filter for high deposition of energy.

Experimental Setup

The experiment was performed at GANIL using ^{40}Ar beams at 27, 44 and 77 A.MeV. The target was metallic ^{232}Th of thickness 0.7 mg/cm². Thorium was choosen because its low fission barrier allows a discrimination against the target recoil from evaporation residue via the mass spectra. The experimental setup is shown in fig. 1, where the z-axis corresponds to the beam direction. The objective behind the setup is to detect the heavy fragments at forward angles via silicon counters (Si). To filter events 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 (30X30cm^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 was typically 0.7ns between the RF and the Si for elastic scattering.

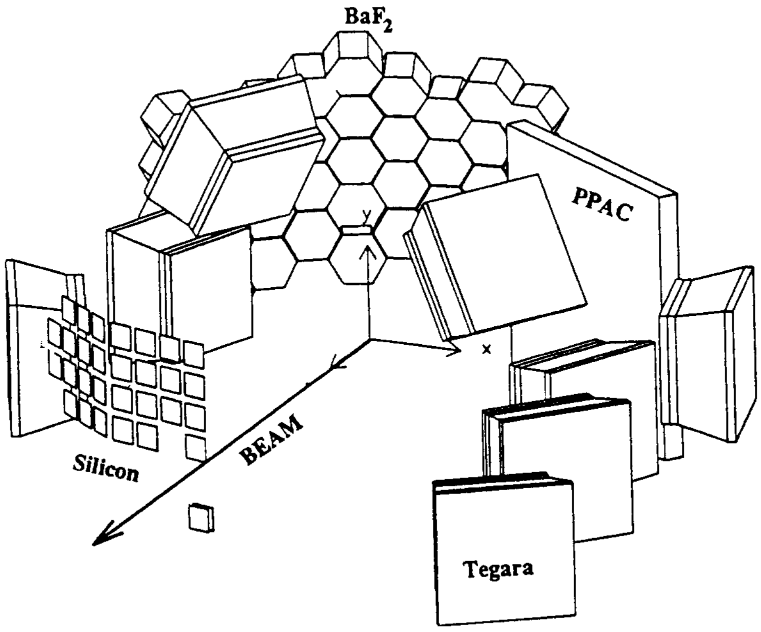

Fig. 1 Experimental set-up.

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 Cf source on a thin backing, the beam and precision pulsres. Energy [6] and time [7] defect corrections were employed to obtain the mass and velocity calibration.

IMF ($3 \leq Z \leq 16$) were detected in 8 ionisation chambers, TEGARA [8], each consisting of a split anode coupled to four 5× 5cm^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 α) were performed with the honey-comb array (fig. 1) containing 36 BaF_2. The crystals were 5cm thick with a cross-sectional area of 25cm^2 [9] and the whole arrangement covered an in-plane angle between -130 and -170°.

Identification of heavy fragments.

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

^{40}Ar + ^{232}Th 44A.MeV

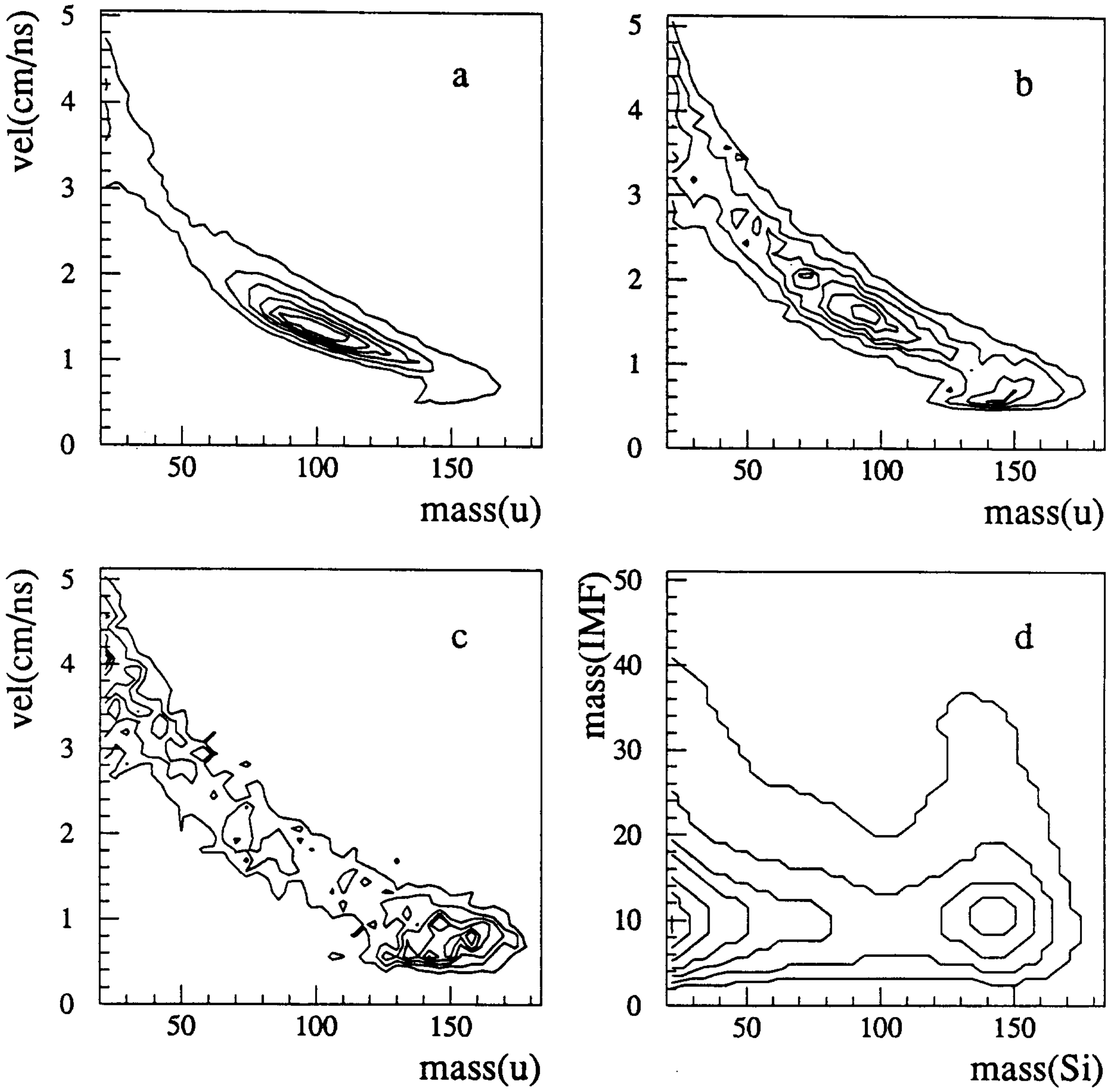

Fig. 2 a) Mass-Velocity in singles mode.
b) as in a) in coincidence with LCP.
c) Mass-Velocity, 8 to 25° in coincidence with LCP and IMF
d) Mass(Si)-Mass(IMF) as for c)

approximately 95 and 160 units of mass. The lower mass peak is attributed to fission from previous measurement [3]. The contribution at 160u, called HF, corresponds to a distribution limited by the velocity threshold of 0.5cm/ns and has a mean velocity, over the distribution 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 27A.MeV there is only a weak presence of HF events. Two comments have to be made; the mass of 160u is approximately 30u smaller when compared to FF correlation data which could suggest a significantly larger deposit of energy for HF events. Unfortunately, as will be seen below, this is not supported by the mean recoil velocity measurement. The other comment is that, what is measured is a falling distribution (only a small hint of a peak at 0.5cm/ns for 44A.MeV) thus giving rise to difficulties in the interpretations.

It is important to note that LCP requirement introduces an enhancement also for masses of about ≈40u. Apart from the physics interest for this mass group, this suggests that the events which are being labelled HF could arise from strongly asymmetric fission. However the mass and velocity spectra for forward Si in coincidence with the PPAC and LCP show no mass contribution at ≈160u when compared to Si-LCP projection. A simulation using the experimental geometry, shows that this result eliminates normal asymmetric fission as a HF production process.

Cross-section evaluation at 44 and 77 A.MeV

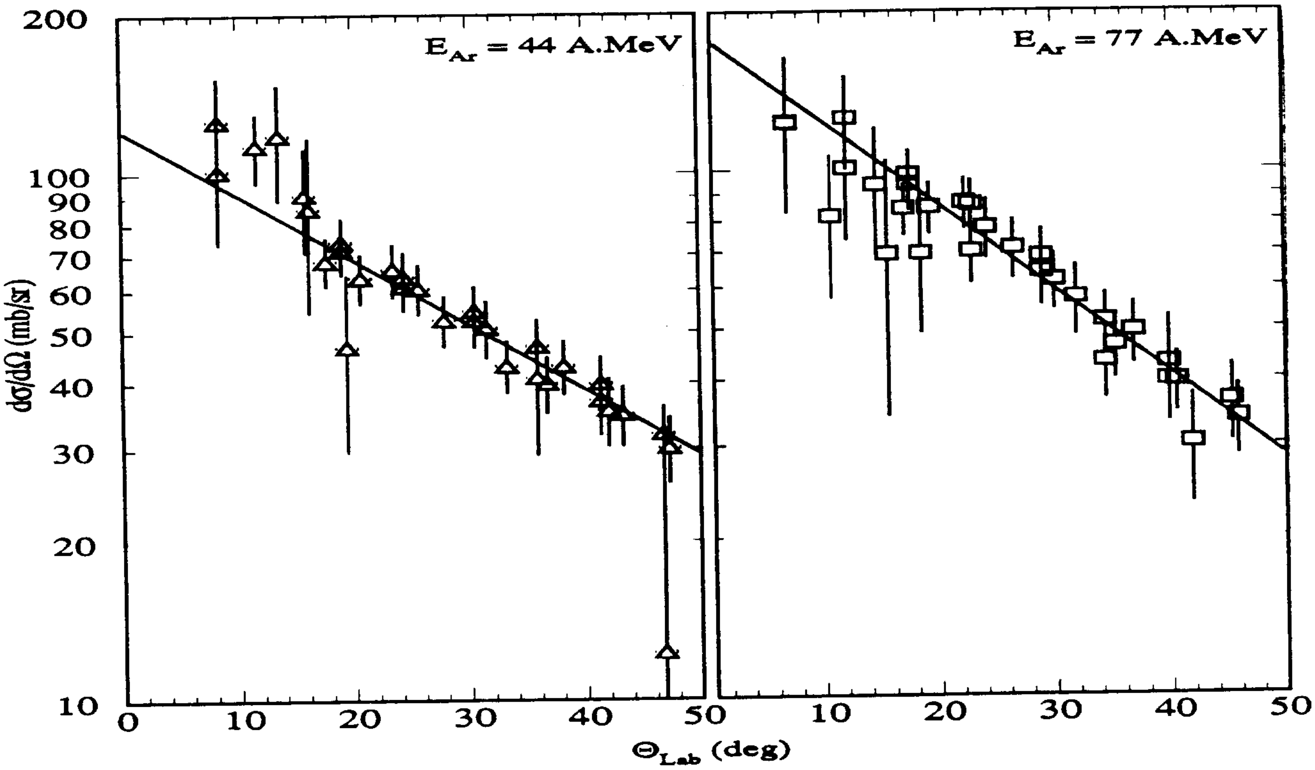

Fig. 3 Angular Distributions for heavy fragments.

To evaluate the cross-sections from the singles measurement a deconvolution procedure was adopted to separate FF from HF in the velocity spectra. To perform this analysis a Gaussian tail was assumed for the HF, whose characteristics were extracted from the coincidence LCP-Si data. The fission component was taken to be Gaussian as suggested from 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 cross-section are given in the table and show that within the given velocity threshold, the cross-section is relatively constant with incident energy. Comparing these values with those of Schwinn et al. [2] shows a good agreement at 44A.MeV but a large variance at 77A.MeV.

Characteristics of heavy fragments

Mean velocity and mass values over the measured distributions were obtained from the Si-LCP correlations and are summarised in the table. Also given in the table, for comparison, are the results of a previous measurement [3,12] from angular correlations for FF for the same system. At 44A.MeV the values are consistent with those of Utley et al. [10]. To depict further the HF, the coincident LCP energy and their multiplicities were studied. 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 alpha spectra are well fitted over the full dynamic range with apparent temperatures given in the table 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 30MeV, reminiscent of pre-equilibrium forward angle data [11]. 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 LCP were assumed to be emitted isotropic in the frame of the HF. The quoted multiplicities are minimal values because no background for the, smaller, FF-LCP multiplicities was subtracted.

IMF- Heavy fragment correlations

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. An analysis, event-by-event shows that the average total mass does not exceed 160u at 44 A.MeV, showing that the rather light masses for the HF are not strongly modified by IMF emission for angles greater than 35°. 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 [11], where beyond 35°, the IMF's have a completely relaxed energy distribution. Therefore, the result imposes that a large fraction of the missing mass and momentum has to escape at forward angles in processes, typical of deep inelastic and/or pre-equilibrium emission. This, in turn might explain the 'shifted' velocity distribution. A remark worth noting here is that Q-value/nucleon for IMFs is practically zero when compared to LCP and neutron emission. Thus, if HF are restrained to decay via IMFs they will tend to have a lower residual mass.

Discussion

The results given above agree with the picture where the HF emerge from a nuclear complex raised at high excitation energy. The neutron [2,10] and LCP multiplicities support this view. As for the apparent temperatures, they are at best average values in a long chain of evaporation, nonetheless they are consistent with high temperatures being reached. Assuming that the HF are indeed evaporation residues, the low mean mass indicates that large amounts of energy are liberated in the long evaporation chain. Further, the tabulated values support the process where at 77A.MeV higher excitation energies are reached. Further, the extracted angular and velocity distributions for the HF are not inconsistent with the evaporation residue hypothesis.

TABLE

Beam Energy	44 A.MeV	44 A.MeV	77 A.MeV
	FF [12]	HF	HF
σ(>0.5cm/ns)	-	290 mb	250mb
<M>	193	160 ± 10 u	145 ± 10 u
<V>	0.9 cm/ns	0.9 ± 0.1 cm/ns	0.84 ± 0.1 cm/ns
M_{LCP}	-	> 6	>7.5
Temp. (α-HF)	-	5.1 MeV	5.0 MeV
E^*_{calc} ⅄	*900 MeV*	*900 MeV*	*1170 MeV*
M_{calc} ✦	*195u*	*195u*	*170u*
Temp. calc	-	*5.3 MeV*	*5.3 MeV*

⅄ corrected for Q-value

✦ ε = 15MeV

To comment on the results and allow an estimate for the excitation energy E^*_{calc}, the simple massive transfer model is employed [12]. It is considered that the HF are evaporation residues and result from a long chain of evaporation which does not, on average, alter the primary recoil velocity. Thus the measured mean velocity is used as input to the calculation. The results of the model are qualitatively consistent with data in that large excitation energies are involved and that higher values are obtained at 77A.MeV. Also, the calculated temperatures (level density parameter assumed to be a constant 8 MeV) are close to the extracted values. Further, the values at 44A.MeV are consistent with extracted E* at 40A.MeV from neutron measurements [10]. However the residual mass does present a disagreement. For the same recoil velocities of the HF and FF it is not possible to adjust ε (the energy removed per evaporated nucleon, normally approximately 15MeV [3]) to give the measured masses at 44A.MeV. Moreover, using the mass transfer from the model and summing the measured masses for HF (FF), LCP, IMF (12u with multiplicity one) and neutrons [2,10] yield a mass deficiency of approximately 20u for the HF and practically no loss for the FF at the same recoil velocity. This discrepancy is not easily explained in terms of a higher excitation in the HF since n-multiplicities for the two, at high LMT, are rather similar [2,10]. Therefore, this indicates that on average the processes involved for the production of HF and FF are different.

Conclusion

In conclusion, the data show 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 [3]. The missing mass and momentum transfer also indicate that processes like deep inelastic and/or pre-equilibrium play an important role in the production of these events. At 27 A.MeV the data indicates that such mechanisms are inhibited. Finally, HF show a selectivity for high excitation, however, a detailed study is necessary to unravel the production process.

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