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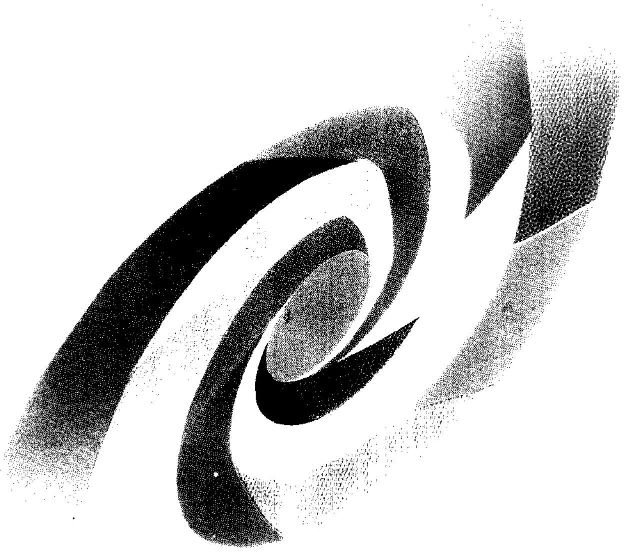

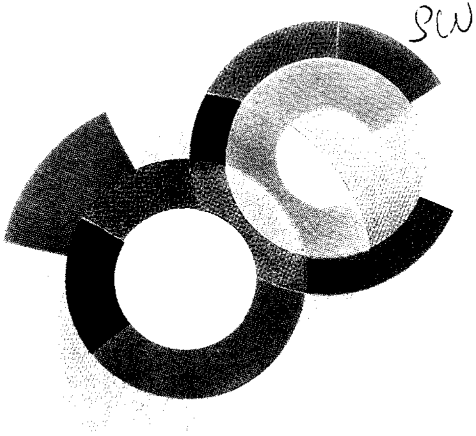

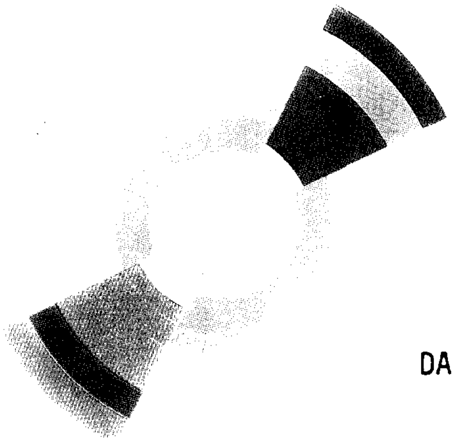

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Abstract

Heavy fragments of mass approximately 150u are observed in the reaction ^{40}Ar(44 and 77 A.MeV)+ ^{232}Th. At 27 A.MeV the yield of heavy fragments is small. The data indicate that the heavy products are formed at high excitation and are accompanied by two intermediate mass fragments, IMF. Boltzmann-Nordheim-Vlasov calculations give a good description and interpret the IMF emission as arising from the overlapping nuclear zone.

The experiment described herein was motivated by a series of measurements which show that in reactions with heavy projectiles, like ^{40}Ar [1,2] , ^{58}Ni [3] and ^{84}Kr [4] on fissile targets, the probability to transfer high linear momentum diminishes with increasing incident energy. The above measurements were performed using a fission correlation technique which requires that two fission fragments are detected. A possible explanation is that the incident channel leads to a nuclear complex that effectively decays via multi-fragment (see G. Westfall's contribution). Whether the process is simultaneous break-up or a series of binary decays, it will lead to privation of in-plane fission correlation. Coming to our motivation, it was considered that given appropriate entrance channel dynamics a large fraction of the incident kinetic energy is thermalized. This results in a copious loss of mass and leads to a composite whose angular momentum, mass and energy will constrain the fission channel, hence, a mean to scrutinize a heavy system at high excitation. Thus we can then refer to the study of the decay of hot nuclei at the limits of excitation, the delicate balance between evaporation residue and fission, limiting temperatures and so. Thus, our study of the reaction ^{40}Ar+ ^{232}Th at 27, 44 and 77A.MeV concentrated on isolating events leading to a very heavy fragment, HF. Selecting the HF allowed us to establish their most probable origin and to characterize some of their properties.

The experiment was performed at GANIL. The target was metallic ^{232}Th of thickness 0.7mg/cm^2. An advantage of having such a highly fissile target is that it allows the target recoils to be distinguished from the evaporation residues through the measurement of mass spectra. The experimental set-up around the target is given in fig. 1. Heavy fragments were detected in a Si array at forward angles. To filter events at high excitation energy, data were captured in coincidence with light charged particles, LCP at back angles (BaF_2) [5]. Similar BaF_2 crystals where also placed at forward angles. Intermediate mass fragments, IMF($4 \leq Z \leq 16$), where detected in 32 ion chambers-Si telescopes, TEGARA, covering a large range of angles. Details of the geometrical coverage is given in [6].

In measuring a velocity versus mass spectra at forward angles we expect [1] to find an island of HF at a mass $\sim$ 190u with velocity typically 1 cm/ns. It is abundantly clear from fig. 2a that the cross section for HF is rather small, with the fission fragments (mass $\sim$90u), FF, having a considerably higher yield. This is true for 44 and 77A.MeV and even more so at 27 A.MeV. It is only by demanding the coincidence Si-LCP($\theta_{LCP} > 140°$) or Si-IMF that the HF become apparent. As seen in the figure, the HF have mass and velocity which are rather smaller than the one expected from full Linear Momentum Transfer, LMT, or from the measured systematics for central collisions (180MeV/c/nucl. of projectile [1–4]). By and large, data for 44 and 77 A.MeV are rather similar, showing only minor differences in the mass of the HF (see tab. I). The yield at 27 A.MeV is very small. To establish the existence of fission contaminant, particularly from asymmetric quasi-elastic events, data were taken in coincidence with a parallel plate (fig 1.) A LCP($\theta_{LCP} > 140°$)-HF-PPAC analysis shows that the HF events do not arise from fission contaminant. HF mean velocity and mass values over the measured distributions were extracted from the Si-LCP correlations and are summarised in table I. At 44 A.MeV the values are consistent with those of Utley et al. [7]. The smaller value of the mean mass at 77 A.MeV would suggest a longer evaporation chain. The average LMT absorbed by the HF is typically 4-5 GeV/c.

The low velocity and the strong presence of fission fragments, FF, makes the extraction of the HF differential cross-section somewhat delicate and reduced due to the velocity threshold. Nevertheless, using an unfolding procedure to separate the fission from the HF [6] and integrating over the measured velocity range give the angular distributions, fig. 3. At 27 A.MeV the cross-section is too small to extract from the singles data. The angular distributions are forward peaked as would be expected from an evaporation residue. The solid line represents a simulation using the evaporation code [8], EVAP, with a nucleus of mass 200u, an excitation energy of 650 MeV, an angular momentum of $80\hbar$ and a recoil velocity of 1.0 cm/ns. The simulation exhibits a fall in differential cross-section inconsistent with the data. The integrated differential cross-section are given in table I and show that within the given velocity threshold they are constant with incident energy. Comparing these values with Schwinn et al. [2] gives a good agreement at 44 A.MeV but a large variance at 77 A.MeV.

The LCP at back angles apart from allowing us to mark the HF, yield energy spectra and LCP multiplicities. The energy spectra for alphas were transformed in the rest frame of the HF and fitted using a Maxwell-Boltzmann function. The fits give apparent temperatures of ~5 MeV at both 44 and 77 A.MeV. The proton spectra have a shape which cannot be fitted with a Maxwell- Boltzmann function over the full energy range. In other words, if we restrict the energy range up to 30 MeV this is a Maxwell-Boltzmann function consistent with 6 MeV. Beyond this range we find an enhancement, reminiscent of pre-equilibrium forward angle data [9]. This enhancement is more significant at 77 A.MeV. To obtain the mean LCP multiplicity from the LCP-HF data, a simulation was undertaken assuming velocity spectra for the HF and LCP distributions which when passed through the experimental filter reproduced the data. LCP angular distributions are assumed to be isotropic in the emitter frame with ratios for p/ d/ t/ ^{3}He/ α adopted from the measured values. The experimental geometry was taken into account using the code GEANT 3.15. Extracted multiplicity values are given in the table I and show a unit enhancement at 77A.MeV. It is considered that the multiplicities are minimal values because no background substraction for the FF-LCP is included. Such consideration does not include variations in the angular distribution of the LCP. To give an order of magnitude, the measured multiplicities can be reproduced by assuming an evaporation residue of mass 230u recoiling at a velocity of 0.8 cm/ns, angular momentum 80$\hbar$ and excitation energies from 650 to 750 MeV. Similar values for the multiplicities and excitation energies are obtained for central collision data [2].

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 striking feature is that the correlation is indeed quite strong with HF. The mass distribution of the IMFs has a somewhat extended range for HF that for fission. Kinematics reconstruction between IMFs and HF gives a strong LMT unbalance of ~50% . For small θ_{IMF} the relative velocity between IMF and HF is higher than the Coulomb repulsion between two spheres, but beyond 48° the IMFs have a completely relaxed energy distribution. It is interesting that although our data do not extend to small enough positive angles, θ_{IMF}, the plot for both the LMT and relative velocity between IMF and HF superimpose those of the Ar+Ag system in a similar incident energy range [9]. The angular correlation integrated over all Z_{IMF} is given in fig. 4 and is forward peaked with an enhancement on the opposite side of the HF ($-8^\circ \leq \theta_{HF} \leq -25^\circ$). Performing HF-IMF correlations with EVAP and parameters noted above, does not reproduce the data (see hashed zone in fig. 4). These results indicate that on average the HF are not evaporation residues but issue of a mechanism reminiscent of deep inelastic collisions, occurring over a large range of incident energy. This is in good agreement with the results of Lips et al. [10] for the ^{40}Ar(31 A.MeV)+ ^{232}Th system and Rivet et al. [9]

Integrating the angular HF-IMF correlations using out of plane results of Lips et al. [10] give an IMF multiplicity of approximately two. To exploit the IMF multiplicity the correlation HF-IMF-IMF was analysed where one of the IMFs is detected in the forward BaF_2($\theta_{IMF} \leq 10^\circ$). The resulting angular correlation is very similar to that for HF-IMF, however with a moderately stronger asymmetry, favouring the angles opposite to the HF angles. The 44 and 77A.MeV data are again similar with the exception that the events at the higher energy have IMFs ($\theta_{IMF} \leq 10^\circ$) which on average are close to beam velocity. Assuming that the forward IMF has mass equal to 10u, the summed momenta of the three fragments yield a mean LMT of ~7.5 GeV/c at 44 and 77A.MeV.

To appreciate the dynamics that are involved in producing the heavy fragments we have considered the Boltzmann-Nordheim-Vlasov, BNV , equation. The calculation allows entrance channel effects ranging from complete to incomplete fusion or deep inelastic reactions to be described [11]. For the present system at 27 and 44 A.MeV, the most important properties (mass A, velocity V_{lab}, predicted excitation energy E^*, intrinsic angular momentum J) of the primary fragments formed through the dynamics are shown in tab. II, III at a time when pre-equilibrium effects have ceased ,T_D , for different impact parameters, b. It is to be remarked that within this time about half of the available energy in the centre of mass is removed through the emission of approximately 30 nucleons. This effect is uniform over b values up to ~7fm [11]. It should be noted here that in the range of b=6-8fm, the properties of the primary fragments given in table II,III are calculated at 180fm/c for, at the equilibration time of 120fm/c they are not yet formed. Therefore the given values include the evaporation between 120 and 180fm/c.

From low to intermediate b values, for 44 and 77 A.MeV a transition from incomplete fusion to 'deep inelastic' mechanism occurs. The 'deep' is characterized by the formation of a HF and two IMFs which originate from the overlapping nuclear zone and the projectile reminant. Unlike at 44 A.MeV, at 77 A.MeV one of the IMFs has close to beam velocities (b = 4-8 fm). Further, the LMT of the three fragments add up to 7-8 GeV/c. These results are in good qualitative agreement with the data. In particular the recoil velocity and the mass after evaporation [8] are also consistent with the data.

The calculations yield HF with low mass and excitation energy thus the fission probability is attenuated. The opposite effect is calculated at 27 A.MeV where essentially two fragments are present in the exit channel producing a relatively heavy fragment with large J and thus overcome by fission (intermediate values of b). Again this offers a good description of what is observed experimentally

A difficulty arises in the predicted E^*. For intermediate b the calculated predicted E^* for the HF are relatively small to reproduce the measured LCP multiplicities. Part of the discrepancy is removed by considering evaporation starting at about 120fm/c. We are studying the possibility that the LCP spectra contain a significant pre-equilibrium in the calculation component, as suggested by the proton data. Also, the nucleon-nucleon cross-section could be adjusted so as to limit the number of pre-equilibrium nucleons.

In conclusion, the data shows that in the ^{40}Ar + ^{232}Th system at 44 and 77 A.MeV, HF are observed and are the products from a nuclear complex at high excitation energy. The neutron [2,7] and LCP multiplicities support this view. As for the apparent temperatures, they are average values in a long chain of emission, nonetheless they are consistent with high temperatures being reached. Further, the HF, HF-IMF and HF-IMF-IMF data at forward

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angles are not consistent with an evaporation residue being formed and interpreted as arising from a highly disipative mechanism at intermediate impact parameters. The cross-sections for HF with the given experimental thresholds are constant with incident energy and even if they were to arise from central collision they are relatively small to explain the missing values [1]. At 27 A.MeV the cross-section for HF is small. BNV calculations are presented and show an IMF emission from the overlap between the projectile and target. The calculations give a good overall qualitative description of the data.

TABLES

Beam energy	44 A.MeV	77 A.MeV
σ_{HF} ($V \geq 0.5$ cm/ns)	290 mb	250 mb
$\langle M \rangle$	150 ± 10 u	140 ± 10 u
$\langle V \rangle$	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

TABLE I. Experimental results

b (fm)	T_D (fm/c)	A (u)	E* (MeV)	J ($\hbar$)	V_{lab} (cm/ns)
4	120	251	463	121	0.93
6	120	253	424	173	0.87
7	180	60	37	32	2.04
		181	0	54	0.57

TABLE II. BNV calculations for ^{40}Ar + ^{232}Th at 27 A.MeV

b (fm)	T_D (fm/c)	A (u)	E* (MeV)	J ($\hbar$)	V_{lab} (cm/ns)
2	120	241	705	72	1.18
4	120	245	684	127	1.14
6	180	5	12	1	3.60
		44	45	27	1.32
		177	178	107	0.90
8	180	5	28	1	7.20
		14	76	3	3.60
		216	26	65	0.48

TABLE III. BNV calculations for ^{40}Ar + ^{232}Th at 44 A.MeV

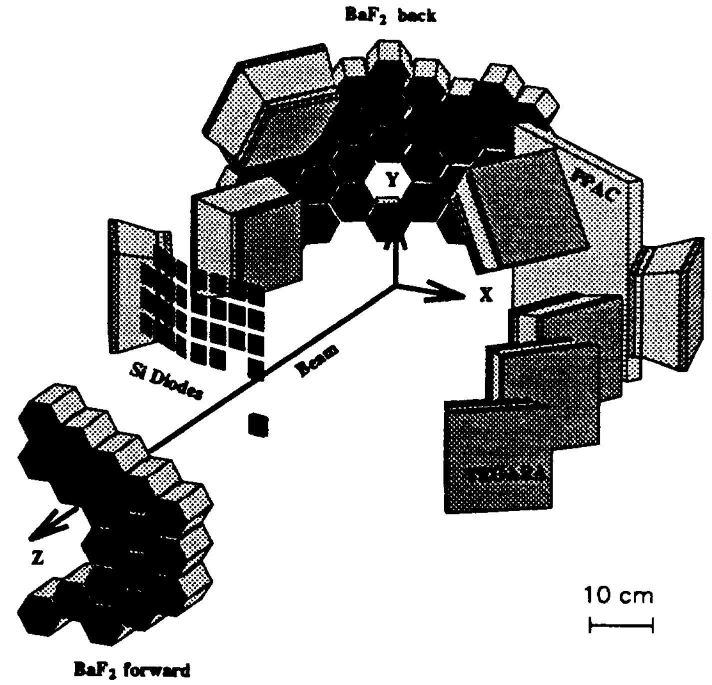

FIG. 1. Experimental Set-up.

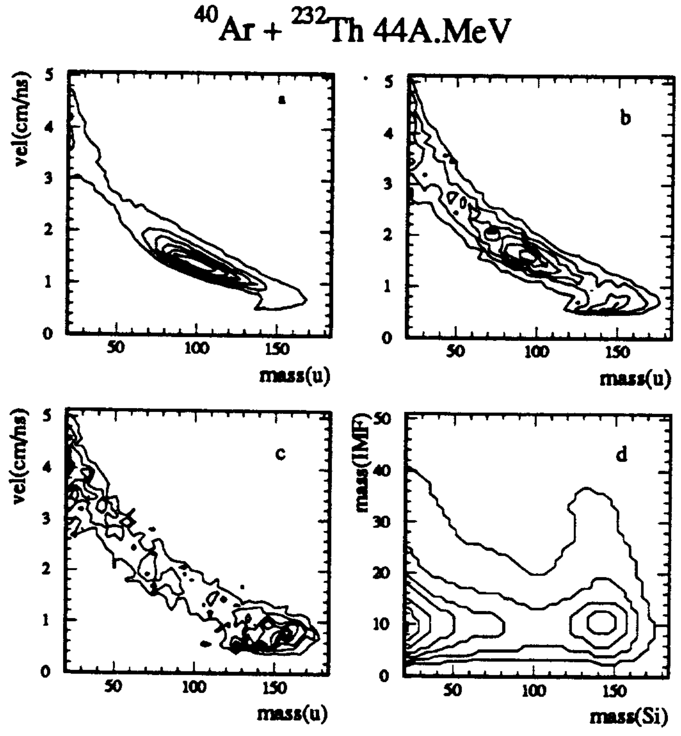

FIG. 2. (a) Mass-Velocity in singles mode in Si.
(b) as in a) in coincidence with LCP.
(c) as a) for angles between 8° and 25° in coincidence with LCP and IMF.
(d) Mass(Si)-Mass(TEGARA) as for c).

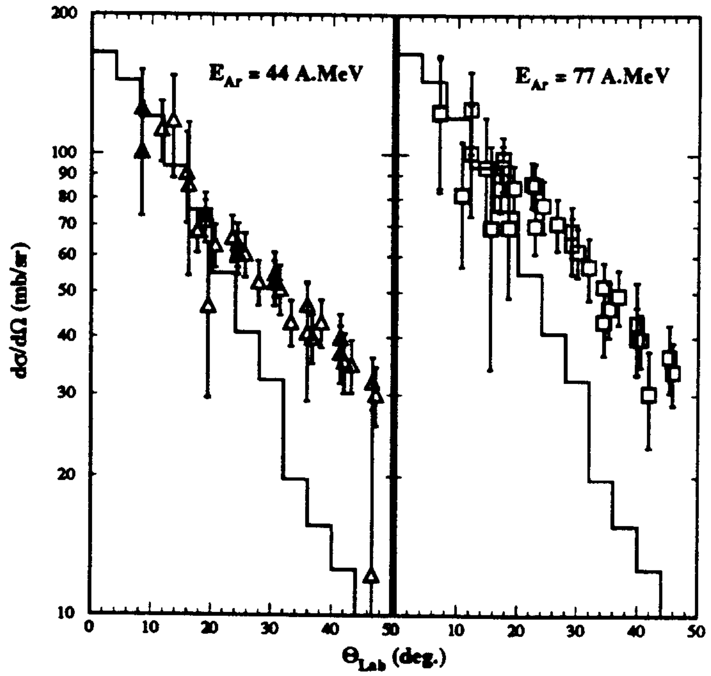

FIG. 3. Angular distributions for heavy fragments. The solid line represents a simulation using the evaporation code EVAP.

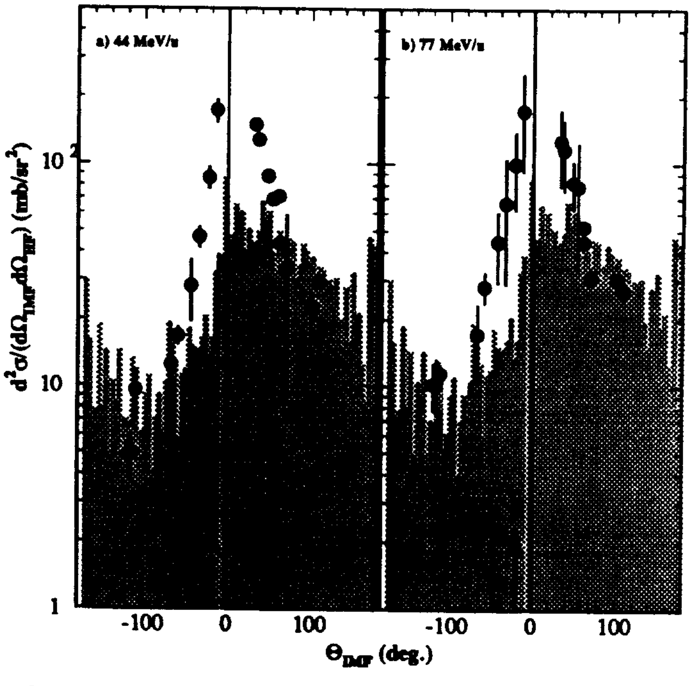

FIG. 4. Angular correlations between HF and IMFs. The HF are detected in the angular range of -8° to -25° (arrow). Hashed zone represents a simulation using EVAP.