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CHARACTERISTICS OF VIOLENT COLLISIONS IN Ar-INDUCED REACTIONS AT INTERMEDIATE ENERGIES

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CHARACTERISTICS OF VIOLENT COLLISIONS IN Ar-INDUCED REACTIONS AT INTERMEDIATE ENERGIES

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Violent collisions have been extensively studied at incident energies lower than 10 MeV/u[1]. They occur for a rather large range of impact parameters and lead to fusion of the incoming nuclei. Complete fusion has been shown to be dominant in this energy range where incomplete fusion processes just begin to appear[2-5]. When raising the incident energy, one can wonder whether such processes will still occur, as the fusion nuclei will receive more and more linear momentum and excitation energy. A rather large set of data has already been obtained with projectiles ranging from He to Ne between 10 and 30 MeV/u, and with ^{12}C projectiles at energies up to 84 MeV/u[6-12]. Most of these works concern heavy systems (target masses larger than 200), and are focused on the measurement of the linear momentum distribution of the fusion nuclei. If one restricts to central collisions, the most probable value of the linear momentum transfer decreases from 95 to 80 % of the projectile momentum as the energy increases from 10 to 30 MeV/u. It means that for this energy range incomplete fusion becomes the dominant process for central collisions. Actually the term "incomplete fusion" does not imply a unique reaction mechanism ; one can imagine several processes. The projectile may break up in the Coulomb field of the target, and part of it fuses with the target. Alternately the total projectile may fuse and then several high velocity nucleons escape, before the fusion nucleus reaches equilibrium. In the following, we will call "fusion-like nuclei" the heavy products formed in central collisions, wether fusion has been complete or incomplete.

The new GANIL facility in Caen has provided the first Argon beams between 20 and 60 MeV/u. As one can expect to transfer more linear momentum and excitation energy with these projectiles because of their substantial mass, these Ar beams seem well suited to address the following questions :

Does the linear momentum transfer (LMT) follow the systematics observed for lighter projectiles ?

Do fusion processes still occur ?

Is there a limit to the temperature, or the excitation energy (or both) that a nucleus can achieve ?

We will report on two experiments performed in our group using the 27 MeV/u Ar beam. The first one concerns an intermediate mass system, Ar + Ag. For the second one a heavier fissile system, Ar + U, was chosen.

For Ar + Ag, information about fusion requires the measurements of evaporation residues and fission. The masses and velocities of the residues were measured by means of a time of flight telescope (carbon foil associated with channel plates - solid state detector). The flight path was 1.25 m. The same telescope was used to derive the characteristics of one fission fragment, while the coincident partner was detected in a large area (20 x 20 cm^2) position sensitive parallel plate detector.

In the Ar + U reaction, most of the collisions lead to fission. The violence of the collision is therefore determined from the correlation angle of the coincident fission fragments. These fragments were detected on one side by four solid state detectors, and on the other side by a position sensitive parallel plate detector. More insight into the reaction mechanism was gained by studying light charged particles emitted in coincidence with the two fission fragments. Six three member solid state telescopes were located between 15° and 160° to record them.

I. LINEAR MOMENTUM TRANSFER

A) For the Ar + Ag system, fusion-like reactions are expected to produce primary residues with mass ranging from 130 to 150. It was shown at lower incident energies that their subsequent deexcitation proceeds partly through particle evaporation and partly through fission. For instance at 8.5 MeV/u, the cross sections for evaporation residues and for fission are roughly equal[4]. In the experiment reported here, we got only a preliminary indication that abundance of fission is smaller than that for evaporation residues[13].

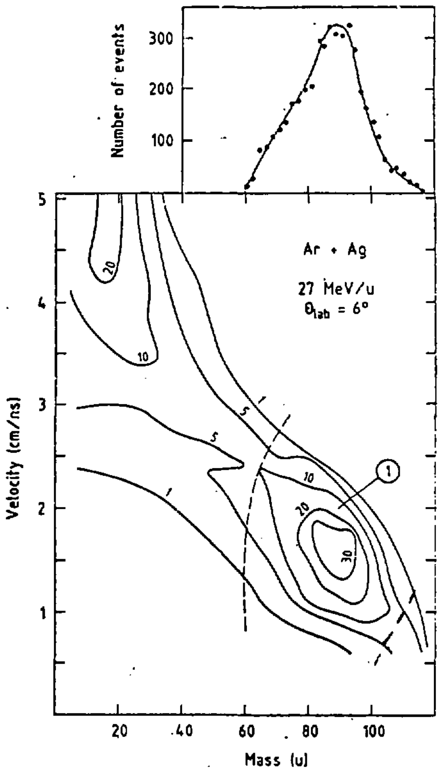
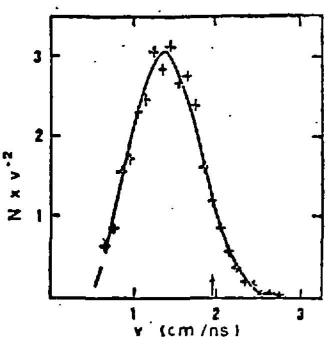


Figure 1

Mass-velocity spectrum of the products measured at 6° in the 27 MeV/u Ar+Ag reaction. The projected mass and velocity spectra correspond to the residue zone (1) only. The arrow indicates the full momentum transfer velocity.



A mass velocity spectrum measured at 6° is shown in fig. 1. Heavy residues from violent collisions appear clearly in the region labelled 1. At this angle the average residue mass is equal to 89 and their average velocity is v_R = 1.40 cm/ns. With increasing detection angle, both v_R and the average mass decrease. At very forward angles, the most probable velocity of the residues can be related to the most probable parallel linear momentum transfer. This was done by considering one possible picture of incomplete fusion which will be kept throughout this paper : it is assumed that part of the projectile (m nucleons), with its initial velocity v_p, fuses with the target. The recoil velocity of the fusion-like nuclei is then

$$v_R = \frac{m\, v_p}{m + m_t} \qquad (1)$$

and their linear momentum

$$p = p_i \frac{m_t}{m_p} \frac{v_R}{v_p - v_R} \qquad (2)$$

In these equations the subscripts p and t refer to projectile and target, and p_i is the total projectile linear momentum.

From the most probable velocity $v_R = 1.40 \pm 0.1$ cm/ns measured at 6°, we deduce the most probable linear momentum of the residues $\Delta p_M = 5.72$ MeV/c or $\Delta p_M/p_i \gtrsim 0.64 \pm 0.06$. We should however regard this value as a lower limit, as we know that heavy residues are not representative of all the violent collisions. Reactions ending up by fission should be taken into account. Preliminary results on the distribution of correlation angles between the two fission fragments indicate that on the average, the fissioning nuclei have received a larger momentum than the residues. Indeed this is not surprising as the fission barriers are rather high in this mass region. Therefore, only the heavier nuclei, with the larger excitation energies will deexcite by fission . This effect may even be enhanced if there is some particle evaporation prior to fission.

We therefore infer that the most probable linear momentum transfer Δp_M for central collisions in the 27 MeV/u Ar + Ag reactions is between 64 and 80 % of the incident value.

B) As for the Ar + U system, most of the heavy nuclei formed in fusion-like reactions are expected to deexcite through fission. Information about their recoil velocity is derived from the measurement of the angular correlation between the two fission fragments.

The correlation angle (θ_{FF}) distribution measured for the Ar + U system at 27 MeV/u is displayed in fig. 2[14]. This distribution has been integrated over the out of plane angle. $\theta_{FF} = 180°$ corresponds to fission of a cold target nucleus, whereas the correlation angle for symmetric fission after full momentum transfer is $\theta_{FF} = 100°$. The distribution exhibits two bumps, separated by a deep minimum. The bump located around $\theta_{FF} \sim 166°$ can be associated with peripheral collisions, and the one at $\theta_{FF} \sim 110°$ with central collisions.

For each correlation angle, and assuming a symmetric mass division, the recoil velocity of the fissioning nuclei has been calcu-

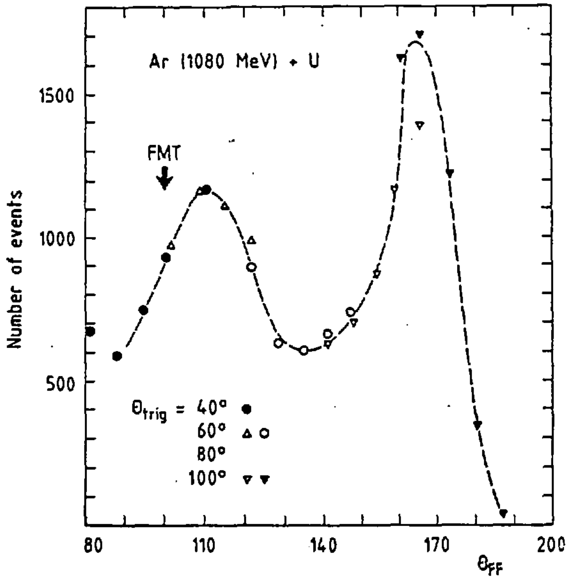


Figure 2

Angular correlation distribution of fission fragments measured for 27 MeV/u Ar induced reactions on ^{238}U.

lated. Then the linear momentum transfer is obtained from eq. 2. The folding angle distribution is therefore transformed into a linear momentum transfer distribution (fig. 3a). The clear separation between central and peripheral collisions makes it easy to deduce the most probable linear momentum transfer for central collisions $\Delta p_M/p_i \sim 80$ % (Δp_M = 7.2 GeV/c).

We found therefore very similar values of the most probable linear momentum transfer corresponding to central collisions for the two systems Ar + Ag and Ar + U. This indicates that Δp_M is essentially independent of the target mass.

C) How does the most probable linear momentum transfer measured in Ar induced reactions compare with results obtained with lighter projectiles at the same energy per nucleon ? We show in fig. 4 the systematic pattern of values found for $\Delta p_M/p_i$ as a function of the relative velocity of the incoming ions[15]. At energies around 30 MeV/u ($v_{rel} \sim 4.8$), the values of $\Delta p_M/p_i$ are around 0.8 for all projectiles between He and Ne. Therefore the values reported here for the two studied systems are very close to the previous ones, allowing an extension of the systematics

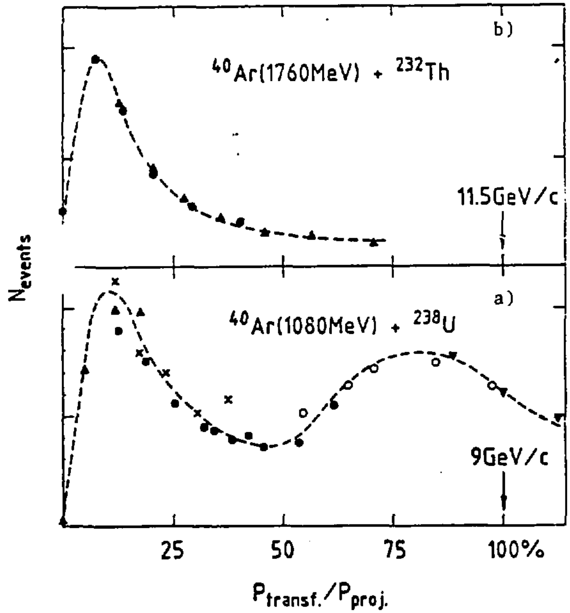


Figure 3

Linear momentum transfer distributions for a) the Ar + U system at 27 MeV/u (ref. 14) and b) Ar + Th system at 44 MeV/u (ref. 17).

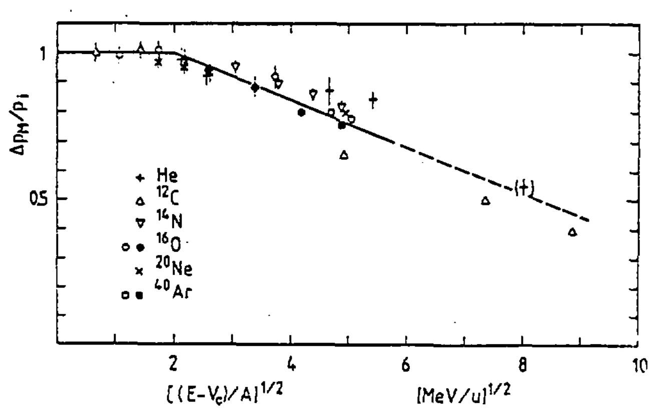


Fig. 4 : Systematics of the energy dependence of the most probable linear momentum transfer measured in reactions induced by various projectiles on actinide targets (open symbols, ref. 2-3,5-11) and on non-fissile targets (black symbols, ref. 12). The lines are to guide the eye.

to projectiles as heavy as ^{40}Ar.

Let us look now at the overall trend of the systematics. The most probable linear momentum transfer remains close to 100 % up to about 10 MeV/u, and then decreases when the incident energy increases, which reflects the growing contribution of incomplete fusion processes. The decrease of $\Delta p_M/p_i$ is approximately linear with the relative velocity. Up to 30 MeV/u, a large variety of projectiles contributes to the systematics (He to Ar). Most of the data concern fissile targets, but besides our point from Ar+Ag other results from residue measurements are also available[12] (black symbols in fig. 4). The systematics below 30 MeV/u show therefore that to first order, $\Delta p_M/p_i$ is dependent on one parameter, the relative velocity ; neither the projectile nor the target mass seem to be of major importance. Above 30 MeV/u the only known data are from reactions induced by He and ^{12}C. The value of $\Delta p_M/p_i$ seems to keep decreasing in a monotonous way.

A possible explanation of this behaviour has been proposed by Grégoire and Scheuter[16]. The decrease of the LMT is predicted by considering the evolution of the dinuclear system (projectile + target) in its momentum space, and the transition from one-body to two-body dissipation. The independence of reaction system would refer to the basic momentum properties of the nucleons inside the nucleus.

Recently some surprising results have been obtained by a French group[17]. The linear momentum transfer distribution was measured for the reaction Ar + Th at 44 MeV/u (fig. 3b). It differs strongly from the one obtained at 27 MeV/u. Indeed only one bump is visible, corresponding to peripheral collisions. For central collisions the systematics shown above predict a value $\Delta p_M/p_i \sim 65$ % ($v_{rel} = 6.2$).

No maximum is visible arount this value, the distribution remains flat in all the region which would correspond to central collisions. This is, to our knowledge, the first system for which this effect appears in the energy domain 10-100 MeV/u.

Obviously the limitation of the linear momentum transfer described above is not sufficient to explain these data. But one should remember that above 30 MeV/u, only He and ^{12}C projectiles have been considered. The Ar projectiles being much heavier will bring more excitation energy to the system, and possibly too much for the fusion-like nuclei to absorb. How is the excitation energy correlated with the linear momentum transfer ? This will be described in the following section.

II. EXCITATION ENERGY OF THE FUSION-LIKE RESIDUES

The excitation energy of the fusion-like residues is expected to increase with the momentum transfer. Data obtained at CERN on the C + U, Au systems between 30 and 84 MeV/u made it possible to derive a more quantitative relation between both quantities[18]. In this experiment the masses of the final fission fragments were measured. The mass loss with respect to the fissioning nuclei is directly related to the excitation energy. We show in fig. 5 the measured mass loss versus the LMT. We observe that at a given incident energy the excitation energy increases with LMT;

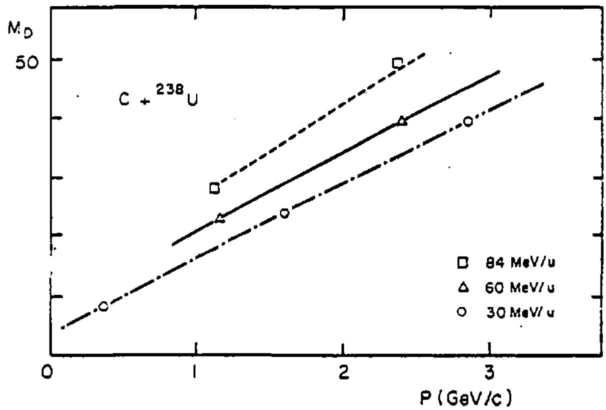


Fig. 5 : Mass loss deduced from the measurement of the final fission fragment masses in the reactions induced by C on U at three energies, as a function of the linear momentum transfer. The lines are to guide the eye.

also for a given momentum, it increases with the incident energy. This is in agreement with incomplete fusion processes where less and less nucleons of the projectile are involved in the transfer process. We indeed demonstrated that there was a very strong correlation between the experimental mass loss and that calculated in the incomplete fusion picture described above (fig. 6).

Can we apply the same description to the reactions induced by 27 MeV/u Ar projectiles ?

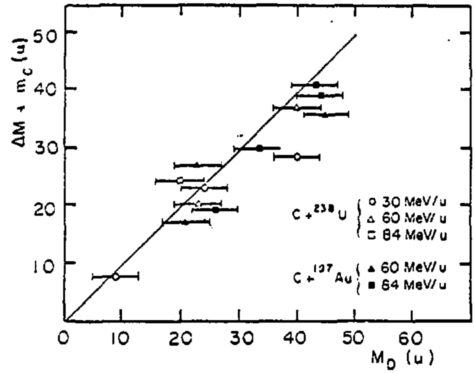


Figure 6

Calculated amount of evaporated nucleons compared to the experimental mass loss displayed in fig. 5.

A) Let us consider first the Ar+Ag system. In fig. 7 are represented the velocity spectra for four mass regions. For masses between 66 and 99, the most probable velocity remains close to 1.4-1.5 cm/ns ; on the contrary it is much lower for the highest mass region, indicating that these residues probably arise from more peripheral collisions ; they were therefore not included in the fusion-like nuclei. For each average recoil velocity we can calculate the mass of the fusion-like nucleus (eq. 1) and its excitation energy ; the latter is shown on fig. 7, where we indicate also the mass loss (number of emitted nucleons). The mass loss increases with momentum transfer, as expected if the excitation energy increases. Another argument showing the increase of excitation energy with the LMT is derived from the width of the velocity spectra for different mass regions. Along with the increase of the recoil velocity, one observes a broadening of the velocity spectrum, as can be expected if more and more particles are evaporated.

We have also indicated in fig. 7 the average energy removed per emitted nucleon. It decreases when the excitation energy increases. This is understood as an enhanced emission of α particles and possibly heavier clusters at high excitation energy. This behaviour is reasonable for the neutron-deficient fusion-like nuclei considered here.

Finally, the characteristics of heavy residues formed in the 27 MeV/u Ar + Ag reactions are consistent with a process in which large excitation energies, up to 750 MeV, are brought to the fusion-like nuclei.

B) We turn now to the Ar + U system. Information on the excitation energy of the fissioning nuclei was derived from the study

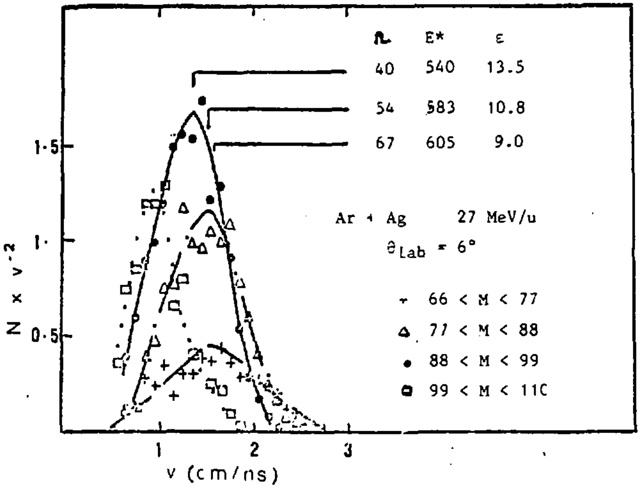


Fig. 7 : Velocity spectra measured at 6° for four mass regions. The excitation energy, mass loss and energy removed per nucleon calculated from the average velocities are indicated for each mass region.

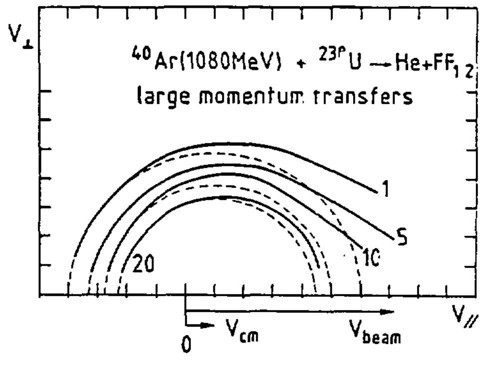


Fig. 8 : Invariant cross sections in the velocity plane of α-particles measured in coincidence with fission fragments in the 27 MeV/u Ar + U reactions. The solid lines represent the experimental iso cross section levels. The dashed circles correspond to isotropic emission from a source moving with the velocity of the compound nucleus V_{CM}.

of the α-particles emitted in coincidence with the two fission fragments[14]. By appropriate gating on the correlation angle of the fission fragments, we selected α-particles emitted in central collisions. We first look at the data presented as invariant cross sections in the velocity plane (fig. 8). This is a convenient representation to look for possible isotropic emission sources. At backward angles and down to ~ 60°, the iso-invariant cross-section contour lines follow circles centered on the beam axis ; the velocity of the emitting source thus deduced is $v = 1 \pm 0.15$ cm/ns, very close to that of the compound nucleus. The ridge of maximum cross-section corresponds, in the source system, to an α-energy equal to 24 MeV. Both the source velocity and the position of the maximum of the α spectra are strong arguments to state that these particles are emitted by heavy nuclei resulting from complete or almost complete fusion of the incident ions. Therefore we conclude that these particles are emitted by the fusion-like nuclei prior to fission, as was found previously for other systems[19,20]. The temperature deduced from the slope of the exponential tails of the spectra at backward angles reflects therefore the excitation energy of the fusion nuclei. In figure 9 are represented the α particle spectra measured at different angles. The dashed lines result from a calculation assuming isotropic evaporation from fusion-like nuclei which have received 80 % of the momentum transfer. The corresponding calculated temperature, $T = 4.5$ MeV, and a barrier to evaporation equal to 19 MeV[21] were used. The agreement with the experimental spectra at backward angles is excellent, which confirms that the fusion-like nuclei emitting these particles had a high excitation energy.

The variation of the particle multiplicity with the correlation angle of the fission fragments gives additional information on the evolution of excitation energy with LMT. It was indeed shown that the multiplicity of these particles emitted prior to fission increased with the excitation energy[19]. If we consider first the backward emitted particles (fig. 10), we observe a strong increase of the multiplicity when the correlation angle decreases, i.e. with increasing LMT. It should be noted that beyond 100°, which is the correlation for symmetric fission after full momentum transfer, the multiplicity remains constant. This confirms that this part of the correlation distribution corresponds to full momentum transfer, the broadening arising from the mass distribution of the fission

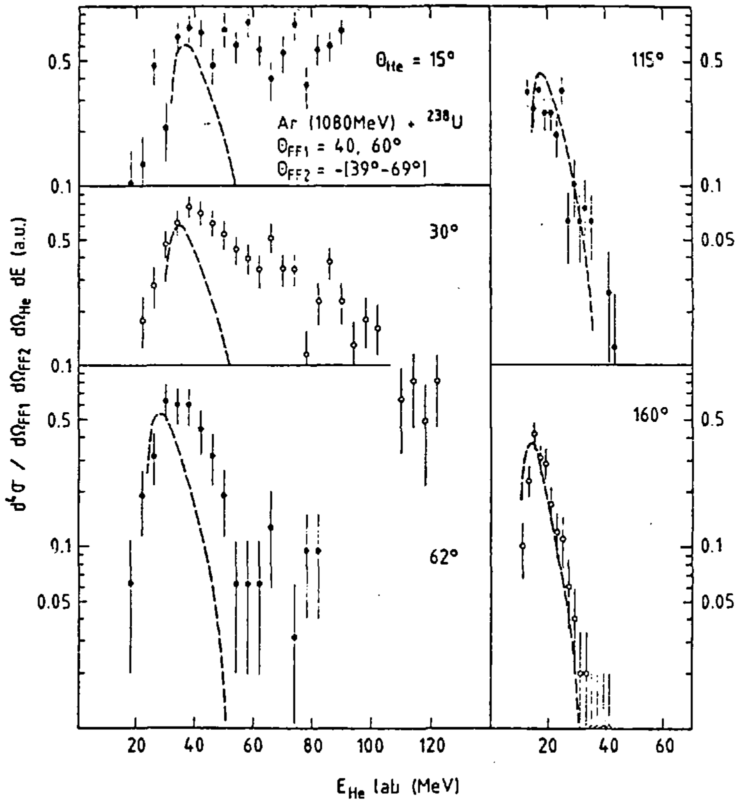


Fig. 9 : Experimental α-particle spectra measured at different angles in coincidence with fission fragments, gated on central collisions only. Spectra calculated assuming Maxwellian isotropic evaporation from fusion-like nuclei (see text) are shown by the dashed lines.

fragments and the large number of evaporated nucleons. Therefore the evolution of particle multiplicity reflects the increase of the excitation energy with LMT, up to the maximum energy $E^* = 800$ MeV which is reached after full momentum transfer.

A surprising effect is observed when looking at the variation of the multiplicity of the particles emitted in the forward direction. Although this point does not directly concern the central collisions, we feel it is worth discussing here. Instead of rising

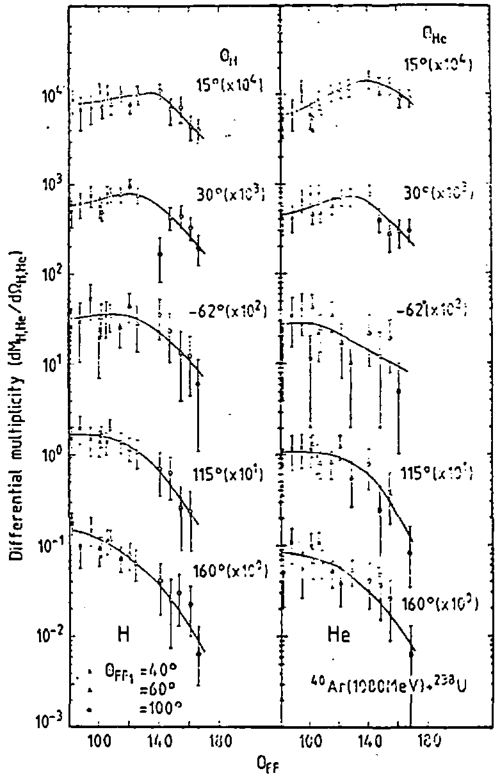


Figure 10

Differential multiplicities for protons and α particles measured at different angles versus the correlation angle of the coincident fission fragments.

continuously with the LMT, the differential multiplicity exhibits a maximum for $\theta_{FF} \sim 140°$; if we look back at the correlation distribution (fig. 2), we notice that it corresponds to collisions at intermediate impact parameters, for which the subsequent fission probability is minimum. A possible explanation for these observations has been suggested from the study of light fragments (Z = 5-12) emitted in the Ar + Ag reactions at 27 MeV/u[22]. For these intermediate impact parameter collisions, the projectile would take away part of the target and form with it a hot participant zone. The target remnant would therefore be a nucleus much less fissile than U, which would explain why fission is not the main exit channel for reactions at intermediate impact parameters. The deexcitation of the hot participant zone proceeds via break-up or emission of a large number of light charged particles and heavier fragment, focused in the forward direction due to the high velocity of the emitters. This can explain the high α particle multiplicity observed.

III. TOWARDS THE LIMITS IN TEMPERATURE OR EXCITATION ENERGY OF A NUCLEUS

We have now shown that very large excitation energies, or temperatures can be reached by fusion-like nuclei. It is interesting to compare these values to some possible limitations of the excitation energy that a nucleus can receive ; recently Campi et al. have compiled a large set of experimental data obtained at energies above 500 MeV/u[23]. They noticed that the mass yields $\sigma(A_F)$ of heavy target remnants (with masses greater than half the target mass) exhibit a nearly exponential behavior. They established a connection between the value of the slope and the number of nucleons lost by the target i.e. the excitation energy per nucleon, ε^*, of heavy residues. With increasing bombarding energy, the slope of $\sigma(A_F)$ first decreases, and then reaches a limiting value.

This means that there exists a maximum excitation energy per nucleon that a nucleus can receive without breaking. The given limit is $\varepsilon^* = 3$ MeV/u, or a temperature of 5 MeV if the level density parameter is taken equal to A/8.

We can test this predicted limitation with the results discussed in this paper.

In the following table we have listed , for different systems, the values of different parameters related to the calculated excitation energy $(E^* = (p^2/2m).(m_t/m+m_t) + Q$, with the same notation as in equations 1-2). The calculation was made for the most probable value of the LMT, and for · full momentum transfer when it was shown to occur, even with a small probability.

For the first three systems, C + U at 30 and 60 MeV/u, and Ar + U at 27 MeV/u, the excitation energy per nucleon remains smaller than 3 MeV. If we reconsider now the Ar + U system at 44 MeV/u, we have seen that, from systematics, the expected $\Delta p_M/p_i$ would be around 0.65.

System	E_{lab} MeV/u	$\Delta p/p_i$	$\Delta p_M/m_p$ (MeV/c)	ε^* MeV/u	T(MeV) a = A/8	E^* (MeV)
C + U	30	0.66	156	0.9	2.65	217
		1		1.3	3.2	319
C + U	60	0.5	167	1.5	3.45	363
		1		2.65	4.6	661
Ar + U	27	0.8	181	2.5	4.5	674
		1		2.9	4.8	800
Ar + U	44	(0.65)	(183)	(3.6)	(5.4)	(950)
Ar + Ag	27	0.73	162	4.3	5.85	600
		1		5.05	6.35	746

The corresponding calculated value of the excitation energy per nucleon would then be $\varepsilon \sim 3.6$ MeV. We have seen that there was very little FF (seen via θ_{FF}) corresponding to central collisions. In the light of the above prediction, we can think that the heavy residues formed in these collisions cannot hold such a high excitation energy, and therefore explode into several pieces much smaller than fission fragments. But let us now examine the last system, Ar + Ag at 27 MeV/u. Here the average excitation energy per nucleon is 4.3 MeV (for the most probable LMT), which is much higher than what was expected in the previous system. Nevertheless, we do observe heavy remnants with the characteristics of fusion-like residues. Why should these last two systems behave differently ? A possible reason can be found if we look at the total excitation energy of the heavy nuclei. It is only about 600 MeV for Ar + Ag (up to 750 for full momentum transfer), and it would reach almost 1 GeV for Ar + U at 44 MeV/u. Therefore, we may think that if a limit exists, it is not on the excitation energy per nucleon (or the temperature), but on the total excitation energy that a nucleus can receive. This is sketched in fig. 11 where we have plotted the most probable LMT for central collisions, $\Delta p_M/m_p$ versus the excitation energy. Fusion-like reactions could occur with a large probability in the region located inside the solid curve.

For excitation energies smaller than 800 MeV and momentum transfer above the most probable value, they still occur but with a strongly decreasing probability. Finally for very high excitation energies the target nucleus could explode under the impact of the projectile, and no momentum transfer can be defined for these central collisions.

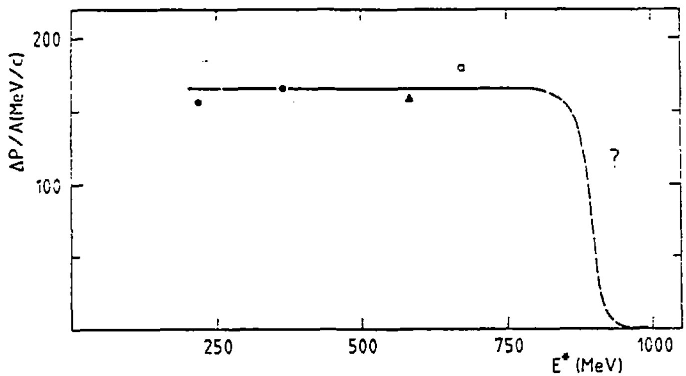


Fig. 11 : Most probable linear momentum transfer for central collisions versus the calculated excitation energy of the fusion-like nuclei. Fusion-like reactions were shown to occur inside the region limited by the solid curve.

We would like to thank the authors of references 13 and 14 for making available their most recent data prior to publication.

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