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LINEAR MOMENTUM TRANSFERS IN LIGHT AND HEAVY ION INDUCED REACTIONS FROM 10 TO 1000 MeV/u

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In this report, the experimental results we obtained on the momentum transfers in the light and heavy ion reactions induced at Saturne [1] (proton, deuton, alpha particle from 35 to 1000 MeV/u),and Ganil [2,3] (^{40}Ar, 44 MeV/u) will be presented. The talk will be concentrated on the three main topics : i) Classification of the reaction mechanisms determined by the average linear momentum imparted to the target nuclei. ii) Evolution of the full momentum transfer probabilities with projectile masses and energies. iii) Limits of the highest momentum and excitation energies which can be transferred to a nucleus.

In most of our experiments, the fission fragment angular correlation technique was used in order to determine the linear momentum transfer (LMT).

I. CLASSIFICATION OF REACTION MECHANISMS.

The average LMT per nucleon $<p_\parallel>/A$ permits to trace the evolution of the nucleus-nucleus interactions in a wide incident energy range without the difficulties to select the fusion-like component when a well-defined bump in the angular correlations does not exist, as it the case for collisions above 35 MeV/u [1]. The measured LMT are good indications of the inelasticity of the reaction mechanism if the fission cross sections σ_{fis} exhaust a large fraction of the reaction cross sections, i.e., for highly fissile target nuclei such as ^{232}Th and ^{238}U up to several hundred MeV incident energies.

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In Fig. 1 the mean LMT per nucleon to such fissile targets are presented versus the projectile energy per nucleon. Reaction Mechanisms can be classified in three regimes :

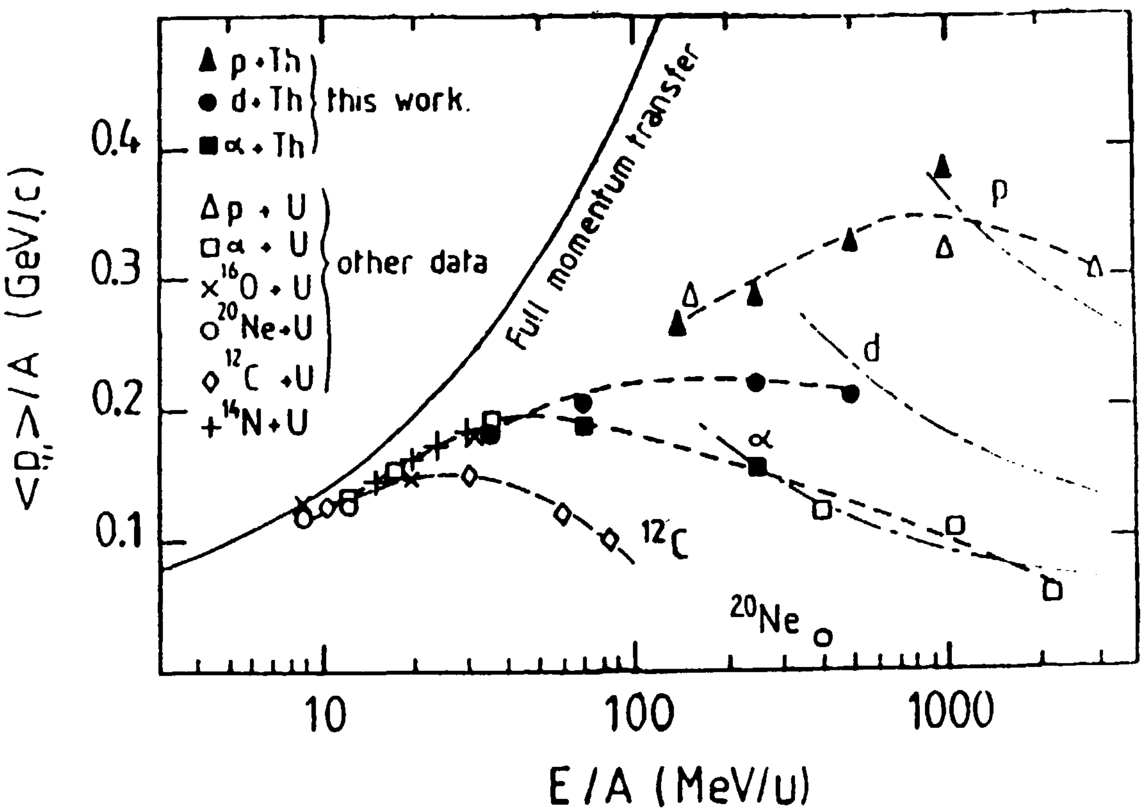

Fig. 1. Average momentum transfer per projectile nucleon versus energy per nucleon. The dashed curve are just to guide the eye ; dotted-dashed curve, see the text.

1. At energies lower than 10 MeV/u, the full linear momentum transfer (FMT) corresponds to the most probable mechanism, i.e., complete fusion and deep inelastic collisions.

2. Between 10 and 70 MeV/u, the data fall below the FMT curve but still more than one half of the incident beam is transferred to the target. Furthermore both light and heavy ion exhibit a scaling up to 30 MeV/u with some deviation for the ^{12}C projectiles. This scaling is preserved for deutons and alpha up to 70 MeV/u but breaks down for ^{12}C ions and ^{40}Ar as will be discussed in sect- n II.3.

3. Above 70 MeV/u, the scaling is lost for all projectiles and the maximum $\langle p_{\parallel}\rangle/A$ depend of the projectile masses. After the maximum

value, $\langle p_\parallel /A$ decreases probably because the target nuclei decay to channels others than fission. For light projectiles at high energies, Porile [4]) derived from intranuclear cascade calculations (INC), an empirical expression $(E^*/E_{CN}) = 0.75(p_\parallel/P_{CN})$, where P_{CN} and E_{CN} are the momentum and excitation energy the compound nucleus would have, if formed. By choosing $E^* = 160$ MeV, one obtains a nice fit of the data above 300 MeV/u incident energies.

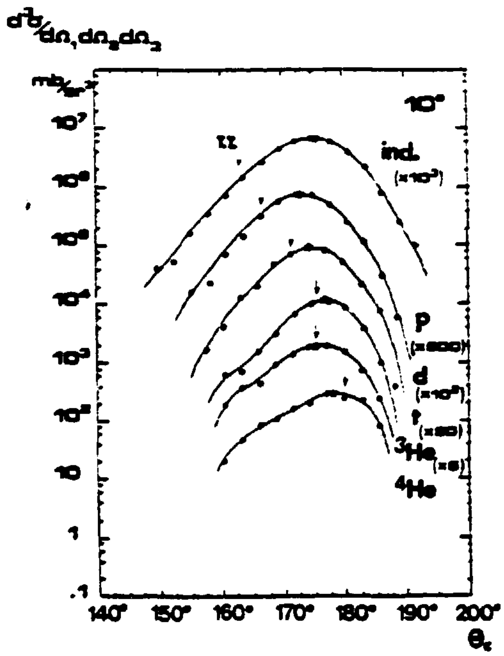

Fig. 2 Angular correlations $\alpha+^{232}Th$ at 70 MeV/u. The curve labelled incl is for fission fragment coincidences only. Curves with p, d, ^3He, α are angular correlations gated by the corresponding ejectiles detected at 10° lab. Points are experimental results and lines are to guide the eye.

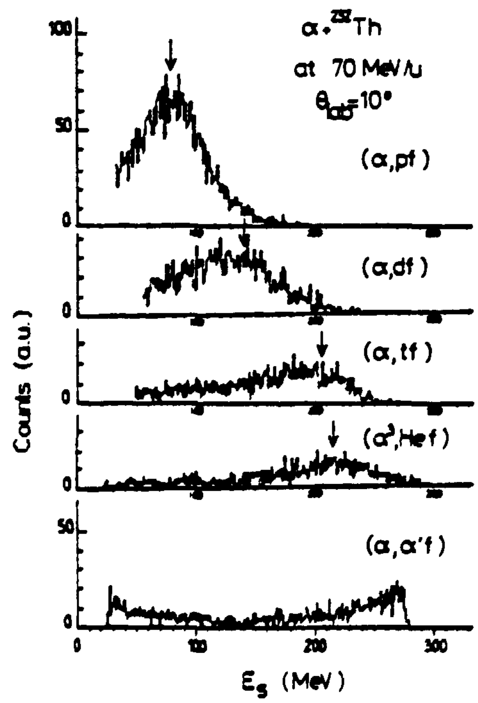

Fig. 3 Energy spectra of the ejectiles corresponding to the angular correlations presented in Fig. 2.

On a per nucleon basis, protons are more efficient to transfer linear momentum than any other projectiles and this result implies an interesting problem for the nucleon-nucleon(n-n) collision model. In this direction INC calculations were performed recently incorporating scattering cross sections of clusters, and Δ resonances in the n-n collisions [5]. However the break-up of the projectile is probably the most important effect and should be included in any quantitative analysis of data.

It has been shown [1] than fission fragment angular correlations give informations not only on mean LMT but also on the LMT distributions produced in the initial target-projectile interactions. These distributions can be studied by detecting ejectiles in coincidences with fission fragments as illustrated in Fig. 2 for the ^{232}Th (α,x fission) at 70 MeV/u [6]. The maxima of the angular correlations move towards larger LMT (small θ_C) when in coincidences with lighter ejectiles, showing that the mass transfer is an important process. However the FMT expected values (arrows in Fig. 2) are not reached even at backward angle (42°) [6]. The coincident light particles are emitted with energy distributions centered around the beam energy (arrows in fig 3). At backward angles the ejectile energies are not centered to the beam energy, but at much lower values corresponding to damped collisions. No missing momentum is observed for (α,tf) and (α,^{3}He f) in average ; then the main process is an absorptive break-up or one nucleon stripping. It is surprising that at a so high velocity, a projectile nucleon can be captured by the target nucleus in peripheral reactions. For the (α,df) process, a missing momentum of nearly one nucleon with the beam velocity is measured whereas it is of one and half nucleon for (α,pf). These results are consistent with recent data obtained recently by Laville et al. [7] for the U(^{16}O,xf) at 31 MeV/u, showing that the angular correlation maxima depend of the transferred masses.

The present body of data allows to determine the gross features of reaction mechanisms and provides a useful guide for future studies.

II. SELECTION OF HIGH LINEAR MOMENTUM TRANSFERS

As we mentionned in the preceding section, the angular correlations on Th and U targets, represent in fact LMT distributions. In this section, we will discuss the way to select the highest LMT values of these distributions.

1) Selectivity with target masses

By choosing, target nuclei with fission barriers higher than for the

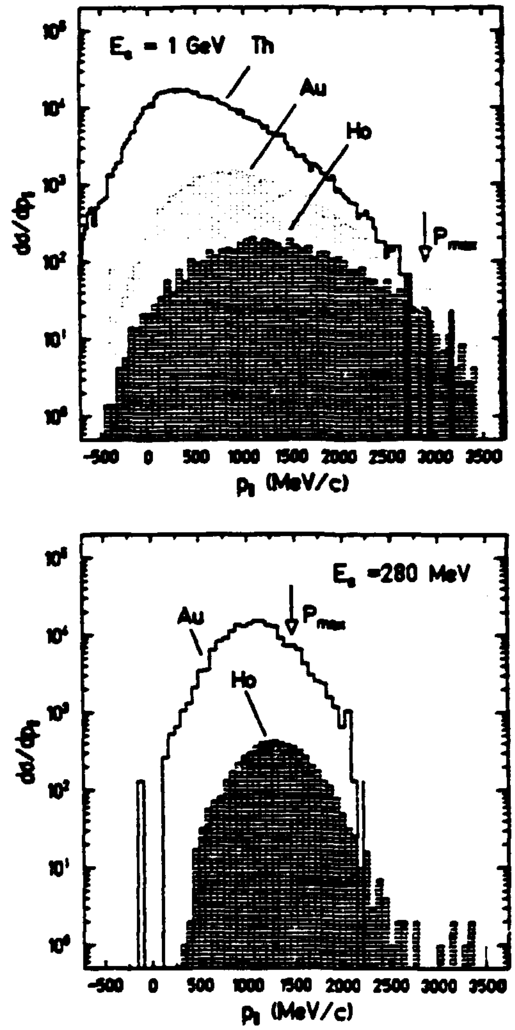

Fig. 4 Fission fragment angular correlations induced by -particles at 280 MeV and 1 GeV, on Th, Au and Ho. Arrows indicate the correlation angle for full momentum transfer.

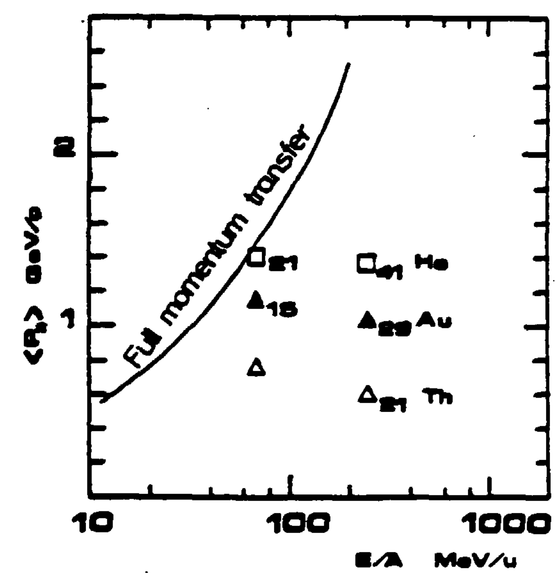

Fig. 5 Total linear momentum versus projectile energy per nucleon. Numbers closed to the target chemical symbol indicate the missing masses.

thorium one, we expect to select more violent collisions with lower cross sections. This selectivity is illustrated in Fig. 4 for the α induced fission reactions on Th, Au and Ho at 70 and 250 MeV/u.

At 70 MeV/u, 90 % of the beam momentum is transferred to the ^{165}Ho target nucleus. On Fig. 5 the $<p_{\parallel}>$ values are plotted versus projectile energy and the missing mass for each target is quoted. One can notice that on Au target nucleus, the $<p_{\parallel}>/A$ is equal to 250 MeV/c whereas 350 MeV/c when using Ho nucleus. So we have to be cautious when claiming for an absolute

LMT-value. However our data show that a saturation phenomenon exist for $\langle p_{\parallel} \rangle$ in the studied energy range. In fact, when increasing projectile energy from 70 to 250 MeV/u, the LMT to a given target mass nucleus does not rise up. More nucleons are ejected during the primary interactions. At 1.25 GeV/u α induced fission on Au [8]), the LMT is dramatically reduced due to the target fragmentation in channels others than fission.

2. Full momentum transfer (FMT)

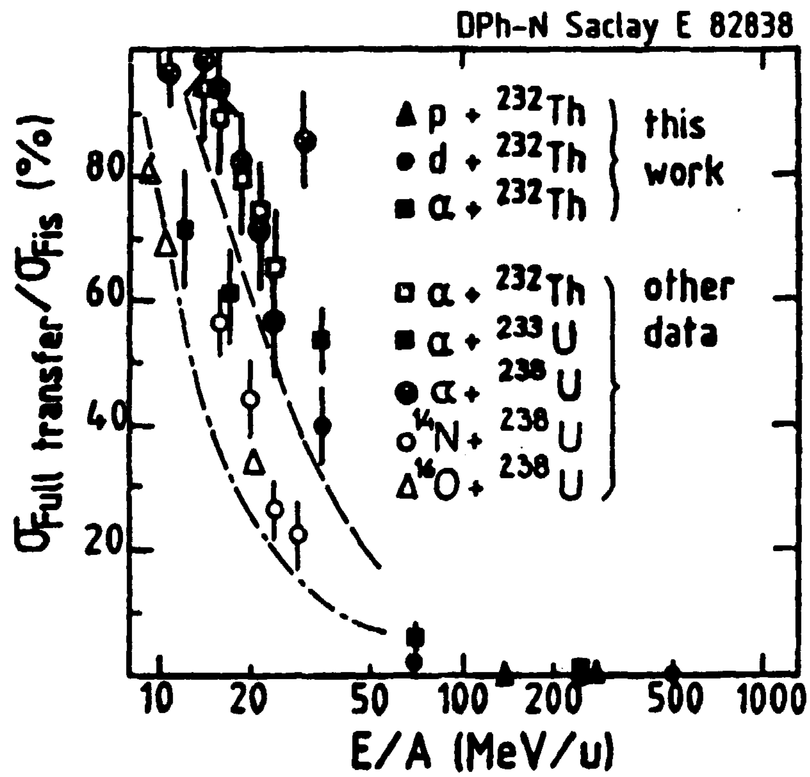

Fig. 6 Full momentum transfer probability versus projectile incident energy. Dotted curve are for α + ^{238}U predictions ; dashed curve is for ^{14}N + ^{238}U predictions.

An important quantity is the probability of FMT which is a necessary condition for a complete fusion-like process. In our light particle data, we defined the FMT probability as a transfer of more than 95 % of the beam momentum and the cross section associated to the FMT, σ_{FT} is extracted from a decomposition of the angular correlation described elsewhere [1]). The σ_{FT}/σ_{FIS} ratio versus projectile energy per nucleon is presented in Fig. 6. This ratio decreases in a rather monotonic way and at 70 MeV/u, it becomes of the order of few per cent. Assuming that σ_{fiss} is closed to

σ_R in this energy region, the predicted values for these ratio performed by W. Wilcke et al. [9]), fit fairly well the experimental results.

Some experimental results have been obtained for heavy ion induced fission [10,11]) using the same procedure as us to determine σ_{CF}. The general trend is similar to the one observed for light ions but at the same projectile velocity the FMT probability is about half of the preceding ones. Once again the comparison is made with the calculated ratio [9]), and the general behaviour is rather well reproduced. For heavy ion collisions leading to complete fusion the $\ell_{cr}/\ell_{grazing}$ ratio is smaller for heavy ions than for light ions at the same incident energy per nucleon.

In studying evaporation residue properties of light systems ($A_{CN} \sim 40\text{-}80$), Morgenstern et al. [12]) achieved a systematic study of complete and incomplete fusion processes up to 20 MeV/u. The $\sigma_{CF}/\sigma_{CF} + \sigma_{ICF}$ ratio has a similar slope as for the σ_{FT}/σ_{FIS} data but the absolute magnitude is lower, and the complete fusion cross section is found equal to nearly zero at 20 MeV/u. To understand qualitatively the probability differences between medium and heavy compound nucleus formation, one may add to the above angular momentum effects, the nuclear temperature influence on complete fusion. At 20 MeV/u of let say ^{12}C or ^{16}O projectiles on a mass target A = 40-50 amu, the compound nucleus temperature reaches already T = 5 MeV while it is only 3 MeV for the compound nucleus A_{CN} = 250 amu, formed with the same projectile velocity.

3. LMT from ^{40}Ar at 44 MeV/u on ^{165}Ho, ^{197}Au and ^{232}Th

Our main objectives in performing these experiments were : what are the highest linear momentum and excitation energy which can be transferred to a nucleus. By performing an event-by-event analysis of the two fission fragment recoil properties(velocity, energy, mass, angle of emission) we deduced the fissionning nucleus velocity as well as its recoil angle and also the fission fragment fission velocity in its center of mass [2]).

Some of the most prominent results are presented in the fig 7. Angular correlations (Fig. 7 a) are peaked at 7 %, 15 % and 35 % of the beam momentum ($p_i \approx 11.5$ GeV/c) for Th, Au and Ho targets respectively. If for Th target this LMT correspond to peripheral collisions with small amount of energy and mass exchanged by the projectile-target system, for Ho target in contrary the LMT corresponds to a quite violent collision.

In our analysis we attach significance to the data of the entire angular correlation and not only to the region where the correlation is peaked. In fact, these angular correlations as for light ions correspond to a LMT distribution since the out-of-plane width (FWHM) is about 12° whereas the studied angular range spread over 100°.

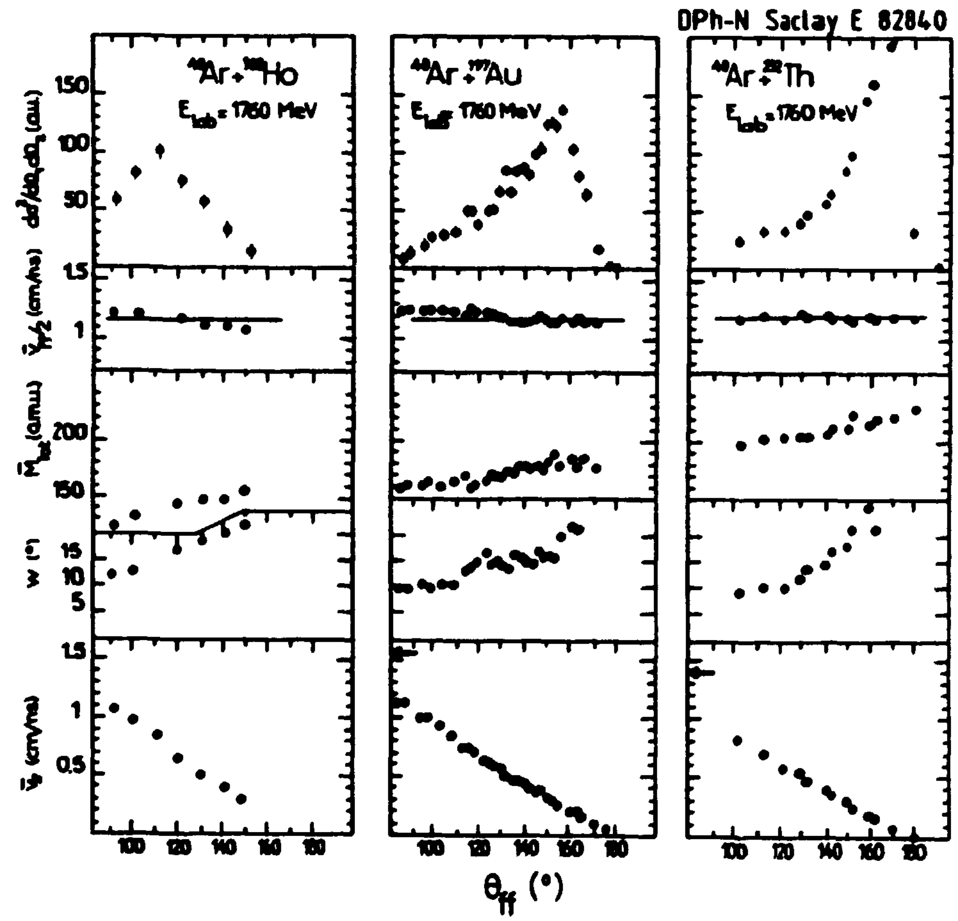

Fig.7 Results for ^{40}Ar + ^{165}Ho (left part), ^{40}Ar + ^{197}Au (midle part) and ^{40}Ar + ^{232}Th (right part). a) in-plane angular correlation between fission fragments. b) average velocities of the fission fragments in the recoil fissioning nucleus frame. The solid lines are from Viola systematics. c) mean total mass of the fission fragments. d) half width at the half maximum of the recoil angle distributions. e) mean longitudinal velocity of recoil fissioning nuclei. The arrow indicates the recoil velocity for full momentum transfer.

The mean half relative speed of the fission fragments $V_{ff/2}$ in their center of mass are presented in fig. 7 b, and compared to the values of the Viola systematics [13]). The agreement is stricking considering that Viola predictions were derived from data at much lower bombarding energies. This agreement suggests that the fission occurs for residual nuclei in the stability valley since a relatively small change in the neutron-proton ratio implies a measurable variation of the V_{ff} values.

The parallel and transversal recoil velocities of the fissionning nuclei were constructed. The $V_{\parallel}$ mean values decrease almost linearly with θ_{ff}, due to the near constant V_{ff}. The half width at half maximum (w) of the recoil angle spectra which are symetric around the beam axis are presented in Fig. 7 d. At low momentum transfer, a small angular deviation of the ejectile ($\theta_{lab} \sim 5°$) induces a recoil angle for the fissioning nucleus of about 30°, then one can understand why the w values are so large at $\theta_{ff} \sim 180°$. At smaller θ_{ff}, i.e., when the LMT increases, one observes a focussing of the recoil angle spectra (w decreases). These events correspond to high recoil velocities of the fissionning nuclei ; one considers these results as indicative that larger and larger fractions of the projectile mass fuse with the target nucleus while the remainder proceeds at forward angle (the remainder part of the projectile mass might not be a whole fragment but also as a shower of light particles emitted at forward angle with the beam velocity). But, whatever the ejectiles, they have to be focussed in the beam axis to be consistent with the measured W values.

From a careful analysis of the data, we can report that for the Ar + Au system the symmetric fission clearly observed at $\theta_{ff} > 80°$ disappears totally at $\theta_{ff} < 75°$. Notice that $\theta_{ff} = 65°$ is the angular location for the FMT.

We interpret the data in a very naive but usual picture. To fit a given value of $V_{\parallel}$, we determine the projectile nucleon number (m) which have to be transferred to the target nucleus ; then one obtains both the recoil momentum of the composite nucleus and its excitation energy corresponding to the complete transformation of the kinetic energy into heat $E^* = E_{CF}\, P_R/P_i (A_T+A_p/A_T+m)$ with $P_R/P_i = m/A_p$; E_{CF} is the maximum energy deposit in complete fusion. P_R and P_i are the transferred and incident momenta. A_T, A_p correspond to the target and projectile mass number respectively). The mass defect is defined as $\Delta A = (A_T + m - \bar{M}_T)$ where $\bar{M}_T$ are the total fission masses measured experimentally (fig. 7c). Assuming that the excitation energy in the compound- like nucleus is evacuated by nucleon evaporation carrying away in average $\varepsilon \sim 15$ MeV/u, then we deduced the predicted ΔA values versus P_R. The relationship between ΔA and P_R is represented by a single full line in spite of mass target differences since they do not induce significant deviations fig. 8. The comparison with the data is quite nice. The excitation energies plotted in the right scale of Fig. 8 is from $E^* = \Delta A \times \varepsilon$. In this framework the highest linear momentum framework the highest linear momentum imparted to a compound-like nuclei in the present experiment is 7 GeV/c corresponding to about 900 MeV excitation energy (T ≃ 5.5 MeV). It is interesting to notice that angular correlations for the ^{232}Th + ^{40}Ar at 27 MeV/u [14]) show a fusion-like bump at 7 GeV/c corresponding in the same picture at 750 MeV excitation energy. But at 44 MeV/u, the cross section is reduced probably because of an increase of projectile fragmentation, higher projectile speed, higher excitation energy etc... which have to be determined quantitatively by a systematic study between 27 MeV/u up to 44 MeV/u of the fission fragments in coincidences with ejectiles.

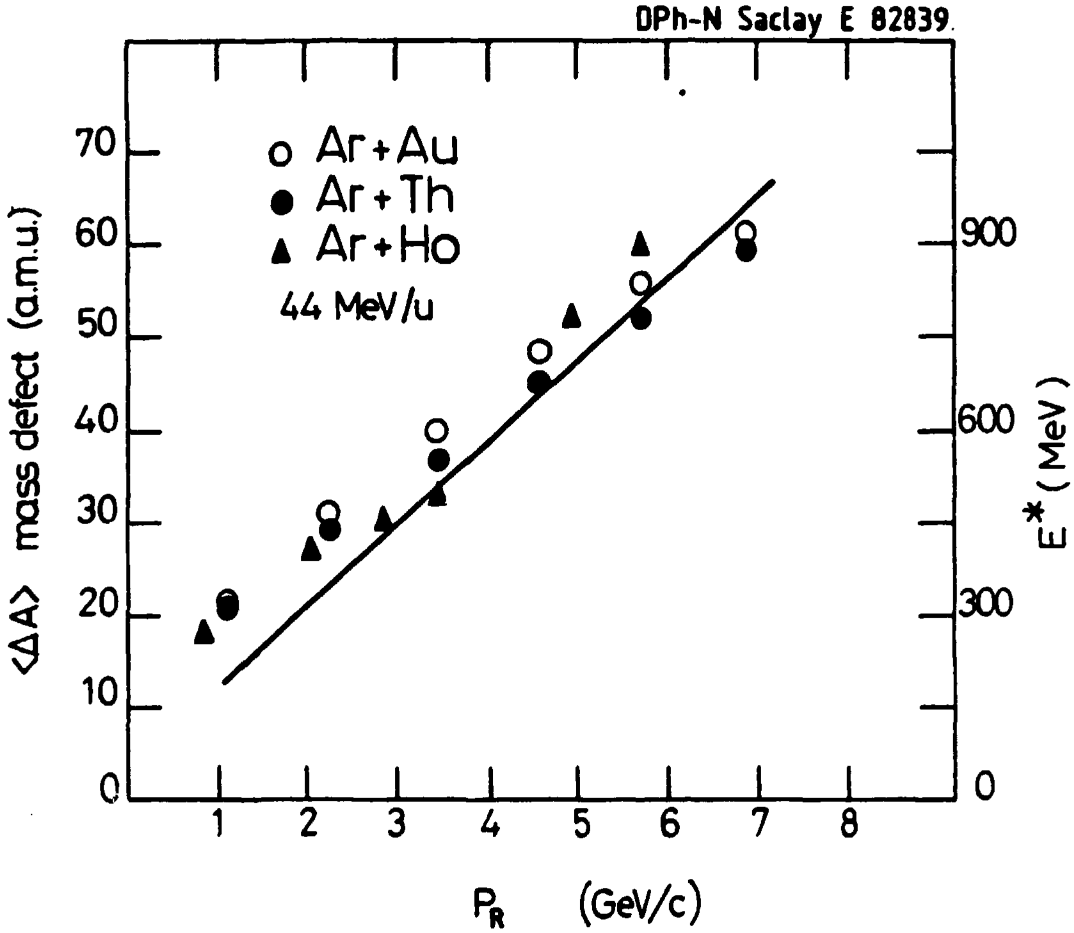

Fig. 8 Missing mass versus the linear momentum transferred to compound-like nucleus in the framework of massive transfer as described in the text. Points are data from different systems and full line in the calculated values.

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