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ABSTRACT

Binary fission of projectile-like nuclei has been investigated in the interaction of 29 MeV/nucleon Pb on Au, together with the associated neutron multiplicity. Fission is only observed in rather peripheral collisions and represents approximately 20% of the total reaction cross-section. The fission process occurs after collisions in which up to 550 MeV have been dissipated. The angular and energy distribution of the fragments can be accounted for by assuming a noticeable spin alignment of the fissioning nuclei.

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* Experiment performed at the GANIL facility

The simultaneous measurement of the dissipation of kinetic energy into heat and of the transfer of relative angular momentum into intrinsic spin has shown to give important information on the reaction mechanism when two heavy nuclei collide with energies close to their barrier.[1-3] When increasing the bombarding energy in the Fermi energy domain, much experimental effort has been devoted so far on the energy damping and comparatively little on the spin observables. However, both aspects are quite complementary and need to be investigated on the same footing if the dynamics of the collision is to be better understood.[4]

In the low-energy experiments sequential fission of one reaction partner has been shown to provide the relevant spin information after measurement of the in and out of the reaction plane distribution of the fission fragments, whereas the energy damping has been assessed from a kinematic analysis of the reaction partners. In this letter we present a novel experimental approach. It is also based on sequential fission, but without explicitely determining the reaction plane. Also, at variance with many previous experiments[5] which have used the kinematical characteristics of the two correlated fission fragments in order to infer the violence of the collision, in the present experiment, we have detected a single fragment and have utilized the neutron multiplicity as a filter on the energy damping. It will be shown that, with such a filter, the main properties of the considered fissioning nuclei can be simply inferred from the measured characteristics (Z, E, θ) of one single fragment, allowing the determination of the dissipated energy and giving evidence for a significant spin alignment. It is also suggested that, by further extending the fission fragment measurements towards the beam direction, a precise determination of the spin value can be achieved.

In a recent paper Piasecki et al[6] have reported on the presence of strong correlations between the character of a collision, between 29MeV/nucleon Pb and Au, and the associated neutron multiplicity, M_n. The latter observable was thus shown to provide a good handle on the violence for a given collision and, therefore, on the associated impact parameter. One can grossly distinguish three main families of events as a function of M_n.

For the lowest Mn (peripheral collisions), projectile-like nuclei are essentially observed, whereas at the other extreme, for the highest M_n (central collisions), mostly light and intermediate mass fragments are measured, indicating a disassembly of the system. For intermediate M_n, one can clearly distinguish a region of nuclei centered around $Z \approx 40$ which are mostly fission fragments of the projectile-like nuclei following a binary reaction, notwithstanding preequilibrium emission or evaporation.

By investigating in some detail the characteristics of these fragments it is possible to gain relevant information on the fissioning nuclei, and this sheds light on the dissipative process for the corresponding impact parameters. By choosing Pb as a projectile, the heaviest beam available at GANIL at the time of the experiment, the most peripheral collisions could not be probed by means of fission (the fission barrier of Pb is ≈20 MeV). As mentioned before, the most central collisions could not be investigated either through this exit channel. The scope of the present study is thus restricted to reactions induced at intermediate impact parameters, for which energies up to several hundreds of MeV are dissipated[7] and large angular momenta are involved ($l_{max}=1700\hbar$).

The experimental set-up has been described previously by Piasecki et al[6]. The fission fragments were detected by means of a position-sensitive telescope subtending a detection angle of 14°, between 6° and 20°. It consisted of two silicon detectors of 24X24 mm^2 (200 μm and 500 μm thick for ΔE and E respectively), each divided into six independent strips, set vertically and horizontally for the first and second member respectively. This set-up provided us with the position of the detected fragment with a precision better than 1 deg.. The good homogeneity of the ΔE detector allowed unambiguous atomic number separation and identification in the range Z=4-48. The rather high energy threshold (18 MeV/nucleon for Z=40), due to the thickness of the ΔE detector, ensured that identified fragments could not arise from the slowly moving target-like nuclei. The neutrons multiplicity was measured both in coincidence with the fission fragments and in the single mode using ORION,[8] a 4π liquid scintillator detector of $3m^3$. The overall detection efficiency computed by Monte-Carlo methods has been found close to 65%.

The Lorentz invariant cross-sections are presented in Fig.1 in the plane of rapidity versus perpendicular momentum for three detected nuclei (Z= 32, 40, 48). These nuclei have been chosen as representative examples of fragments originating from binary fission of the projectile-like nuclei. The fragment of Z=40 corresponds roughly to a symmetric break-up of the quasi-projectile nucleus, whereas Z=32 and 48 delineate roughly the full width at half maximum of the Z distribution. The fragment velocities have been determined by assuming for each Z, a mass A close to the valley of stability using the parametrization[9]: $A=2.08Z+0.0029Z^2$. The data are presented for four different bins in neutron multiplicity between 5 and 44 (as they were registered i.e. without any efficiency correction). Taking the same fission fragment masses for the different bins introduces an uncertainty dA/A of about 10%. Consequently, the uncertainty on the velocity is at least 5%. As pointed out earlier[6], reactions leading to as many as 60 neutrons have been detected during the experiment, but then, most of the associated nuclei are much lighter than the fission-like fragments. Fission-like fragments are mostly associated with detected neutron multiplicities, M_n, not greater than about 45. However, when approaching these multiplicities of 45, the Z distribution strongly broadens with its centroid shifted towards increasingly lighter Z's indicating a strong mixing of fission fragments with nuclei from a different origin.

As long as M_n remains smaller than 35, the data points generate typical ring patterns, often referred to as Coulomb rings whose radii are close to the predictions of the Viola systematics[10] for fission of a Pb-like nucleus. For M_n >35, the circular character of the pictures persists but the rings become blurred. The origin of this evolution will be discussed later on. In addition to these features it must be noticed that for the lightest Z's another component grows up at small angles, besides the well distinct ring. The lack of detection at even smaller angles does not allow any definite conclusion on the origin of such events, however, a plausible explanation for this additional component will be proposed later on.

As shown elsewhere[11] the kinematical characteristics of the fissioning projectile-like nuclei can be inferred from the ring parameters (position of their center and radius). A simple procedure has been followed in order to first locate the maxima on the invariant spectra, measured at different angles, and then, to fit all the thus generated data points by a circle. The resulting parameters, the velocity of the projectile-like fissioning nucleus and its scattering angle, are shown in Fig. 2 as a function of the fragment Z for the three neutron multiplicity bins for which Coulomb rings are unambiguously observed. It is shown in Fig.2-a that the projectile-like velocity remains constant, within the estimated error bars of 5%, as a function of Z for a given neutron multiplicity bin. Indeed one does not expect any dependence on the mass asymmetry of the splitting. It is worth noting that for the lowest neutron multiplicity gate the fissioning nucleus approaches the beam velocity as expected for a rather peripheral collision. Then the larger M_n the more slowed down the projectile-like nucleus appears to be. But even for the most dissipative collisions leading to fission, the fissioning nucleus keeps a high velocity (>7 cm/ns) as compared to the center of mass velocity (3.8 cm/ns) or to the expected velocity for a Pb-like nucleus following a totally damped collision (5.2 cm/ns). The rather peripheral character of the corresponding collisions is thus confirmed both by the high source velocities and by the moderate associated neutron multiplicities. It must be reminded that in the most peripheral collisions (the smallest M_n) the Pb-like nuclei are observed as residues[6] because of their large fission barriers.

From the deduced velocity of the fissioning nuclei and assuming two body kinematics (with a projectile- and a target-like nucleus) preceding sequential fission of the projectile-like nucleus, one can derive the amount of dissipated energy. The deduced dissipated energies for the first three considered gates amount to 150, 360, 550 MeV on the average. Taking into account the nearly symmetric entrance channel this would correspond to roughly 75, 180 and 275 Mev excitation energy in the fissioning nuclei. These energies remain far below the 3 GeV energy available in the system and once again this stresses, for a reaction induced at about 30MeV/nucleon, the rather peripheral character of such collisions. The dissipated energies can be roughly translated into a number of evaporated neutrons by assuming that each neutron carries away about 12 MeV of excitation energy. Indeed it has been shown elsewhere that, at moderate excitation energies, charged particles do not contribute significantly to the decay from heavy nuclei.[12] For each neutron gate one verifies that the kinematically deduced neutron multiplicity matches reasonably well the measured neutron multiplicity after correction for detection efficiency. These features give additional confidence that the masses assumed to get the velocities cannot be far off the actual ones.

The second parameter characterizing the fissioning nuclei deduced from the centers of the circles is their deflection angle with respect to the beam direction (Fig.2-b). The estimated uncertainty on the derivation of θ, $\delta\theta=\pm1$deg., is small enough to show that the average deflection angle is markedly different from the beam direction and slightly inside the grazing angle (6.2 deg.). Due to this large deflection angle the edge of the symmetric ring, centered on the other side of the beam with respect to the beam axis, can contribute to the strong population of events detected at the smallest explored angles. It can be noted that, due to the limited angular coverage, the edge of the ring could only be observed when the ring radius was large enough, i.e. for the lighest fragments.

It is remarkable that the ring pattern could be preserved with a fissioning nucleus recoiling in a direction distinct from the beam axis since smearing effects are then expected. As will be demonstrated in the following the persistence of this pattern gives support to strong spin effects. Such effects are expected in peripheral collisions when l_{max} is as high as $1700\hbar$. These effects on the distribution of the fission fragments have been investigated by a Monte Carlo approach that will be exemplified in the case of fragments with Z=32 gated by M_n=25-34. For the sake of simplicity no relativistic corrections were taken into account in both the calculations and corresponding experimental data. The characteristics of the fissioning nuclei were taken as they were determined from the fitting of the corresponding data i.e. with V_{PLF}=7.07 cm/ns and Θ_{PLF}=4.5deg. The fission fragments were given an average velocity of 1.4 cm/ns, as deduced from the Viola systematics, with a gaussian distribution as known from spontaneous fission (FWHM=30% of the mean value).[13] Then, two extreme assumptions have been made in order to distribute the fragments in their emitter frame. On one hand, spin effects were fully neglected and accordingly isotropic distributions were given to the fragments. On the other hand, the spin effects were assumed to be very strong, with full alignment of the spin vector perpendicular to the reaction plane and the fragments were isotropically distributed, but in this reaction plane only. The results of this simulation are presented in Fig.3 together with the experimental data. For the sake of comparison, all experimental thresholds (in E and θ) have been shown on the simulated data of Fig.3. It is immediately seen that the strong alignment hypothesis is much more appropriate than the low spin hypothesis in order to reproduce the data qualitatively. Spin alignment in peripheral collisions has already been reported by Asahi et al.[14] at 60 MeV/nucleon bombarding energy, but for much lighter interacting nuclei.

Can one assess spin values from the present data? More complete calculations have actually been performed as a function of the usual $(I^2/2K_0^2)$, where I stands for the spin of the fissioning nucleus and K_0 for the projection of I on the fission axis[15]. When assuming for Pb-like nuclei K_0^2 values of about 100 it is found that any spin value larger than 40ħ can grossly account for the available data. A glance at Fig.3 shows clearly that we lack sensitivity in the absence of experimental data at angles smaller than 6 deg.. Therefore the determination of I relies more on the "thickness" of the ring at large angles rather than on the anisotropies which remain weak, in any case, close to 90deg. in the system of reference of the fissioning nucleus.

In the simulation a delta function was given to the scattering angle of the fissioning nucleus, thus reducing the thickness of the rings. If one allows some spreading in this angle, either because of the scattering process itself, or because of the unability of the measured M_n to select a well defined trajectory, then we would need larger spin values to reproduce the data. As a consequence the value of 40ħ should be taken cautiously as a lower limit only.

Returning to the experimental data of Fig. 1 it appears that the ring pattern is best observed for the lowest neutron multiplicities and it becomes smeared at high multiplicities. These results could be interpreted as a loss of spin alignment. As a matter of fact other effects can also blur the spin effects. The first one is linked to the influence of temperature: the thermal fluctuations as well as the evaporation of light particles emitted either prior or after fission[16] tend to broaden the fission fragment distributions out of the reaction plane. The higher the temperature the larger the broadening is expected to be. The second effect is related to the dynamics of the collision. As discussed earlier average deflection angles and velocities of the projectile-like fissioning nuclei have been determined, but not the fluctuations around the mean values. The more inelastic the collisions the larger these fluctuations are known to be.[17] It can be easily guessed from Fig.3, that such trajectory fluctuations can blur the ring pattern. The uncertainty in the mass distribution can also be a factor of broadening. The present data do not allow to properly quantify all the previous sources of smearing. It is expected that the effects of the dynamics could be disentangled in forthcoming experiments by imposing constraints on the determination of the reaction plane.

The last information deduced from these data are the differential cross-sections $d\sigma/dZ$ (Fig. 2c). These cross-sections have been integrated over the measured part of the rings and complemented for the missing part by assuming an isotropic distribution in the reaction plane. They exhibit gaussian shapes roughly centered at half the projectile Z. The small downward shift of the average Z value with increasing M_n mainly reflects the onset of charged particle emission when the dissipated energy increases.[12] Indeed for such a nearly mass-symmetric system in the entrance channel no drift in mass is expected for the projectile-like nucleus, but only a broadening.[17]

The fission cross-section integrated over neutron multiplicities smaller than 35 amounts to σ_{min}=880±170 mb. This value represents a lower bound since binary fission has not completely vanished for even higher neutron multiplicities. However, for $M_n>35$ the Z distributions become so broad that it is difficult to disentangle binary fission events from IMF's on one hand and from possible projectile-like residues on the other hand. Therefore an upper limit of σ_{max}=1230±240mb has been determined by integrating in the bin $35<Mn<44$ all fission-like events, assuming for them a fully isotropic distribution. This represents about 20% of the reaction cross section.

In summary fission of the projectile-like nucleus has been investigated in the collisions of 29 MeV/nucleon Pb on Au as a function of impact parameter by utilizing the multiplicity of accompanying neutrons. Fission occurs for rather peripheral collisions with no more than 20% of the reaction cross-section. For the most peripheral collisions the projectile-like nucleus ends up as an evaporation residue and for the most central ones the whole system breaks up into many pieces.[6] The kinematical characteristics of the fission fragments as a function of neutron multiplicity provide direct information on the projectile-like nuclei from which they are emitted. The fissioning nuclei are focused at angles close to the grazing angle. The primary reaction is binary and resembles very much a deep inelastic collision when it is induced at energies close to the interaction barrier. The ring pattern of the invariant cross-sections of the fragments in the velocity (or rapidy) space bears the unmistakable signature of significantly aligned fissioning nuclei, with spin values larger than 40$\hbar$. As already shown elsewhere[18] this type of peripheral reactions appears to be very promising to generate moderately excited nuclei in high spin states and with expected narrow spin distributions in contrast with what is reached in the more conventional compound nucleus method. Last but not least, the simultaneous measurement of energy dissipation and spin should bring sensitive constraints when testing dynamical collision models.

References

1 P.Dyer et al., Nucl. Phys. **A322**, 205 (1979)

2 D.V.Harrach et al., Phys. Rev. Lett. **42**, 1728 (1979)

3 J.C.Steckmeyer et al., Nucl. Phys. **A427**, 357 (1984)

4 T. Ethvignot et al., Phys. Rev. **C43**, 2035 (1991)

5 S.Leray, J.Phys. (France) **47**, 275c (1986) and references therein

6 E. Piasecki et al, Phys. Rev. Lett. **66**, 1291 (1991)

7 M.Morjean et al., Nucl. Phys. **A524**, 179 (1991)

8 J.Galin et al., in Proceedings of the Second IN2P3-RIKEN Meeting on Heavy Ion Collisions, ed. by B.Heusch and M. Ishihara (Word Scientific, Singapore, 1990) p102

9 R.J.Charity et al., Nucl. Phys. **A483**, 371 (1988)

10 V.E. Viola Jr., Nucl. Data **1**, 391 (1966)

11 L.G. Moretto et al., in *Proceedings of the symposium on Nuclear Dynamics and nuclear Disassembly* , ed. by J.Natowitz (World Scientific, Singapore, 1989) p157 and D.R. Bowman et al., Nucl. Phys. **A523**, 386 (1991)

12 X.Jiang et al., Nucl. Phys. **A503**, 560 (1989)

13 Neiler et al., Phys. Rev. **149**, 894 (1966)

14 K. Asahi et al., Phys. Rev. **C43**, 456 (1991)

15 L.C.Vaz, J.M.Alexander, Phys. Rep. **97**, 1 (1983)

16 D. Hilscher et al., Phys. Rev. Lett. **62**, 1099 (1989)

17 R.J.Charity et al., Z.Phys. **A341**, 53 (1991)

18 D. Jacquet et al., Nucl. Phys. **A511**, 195 (1990)

Figure captions

Fig.1. Density plots in logarithmic scale of the Lorentz-invariant cross sections, $Ed^3\sigma/d^3p$, in the (rapidity-perpendicular momentum) plane for Z= 32, 40, 48 and neutron multiplicity gates M_n=5-14, 15-24, 25-34, 35-44. The upper part of the Fig. corresponds to $\phi=0$ and the lower to $\phi=180$ deg..The data have been symmetrized with respect to the rapidity axis.

Fig.2. a) Average recoil velocities of the projectile-like fissioning nuclei as a function of the detected fragment Z and associated neutron multiplicity M_n.

b) Average deflection angle.

c) Differential fission cross-sections, with the solid lines as gaussian fits.

Fig.3. Monte-Carlo simulations (3-a-c) for Galilean-invariant cross-sections, $d^2\sigma/(v^2 dv d\Omega)$, versus $v_{\parallel}$ and $v_{\perp}$ of fission fragments of Z=32 emitted at v=1.4 cm/ns from a fissioning nucleus recoiling at 4.5 deg. with v=7.07 cm/ns. In Fig. 3a, fission is assumed to be isotropic in the reaction plane (high spin and strong alignment approximation), whereas, in Fig. 3c, isotropic fission is assumed in full space (low spin approximation). The measurable part of the data is delineated within the solid lines in order to facilitate the comparison with the experimental data of Fig.3b.

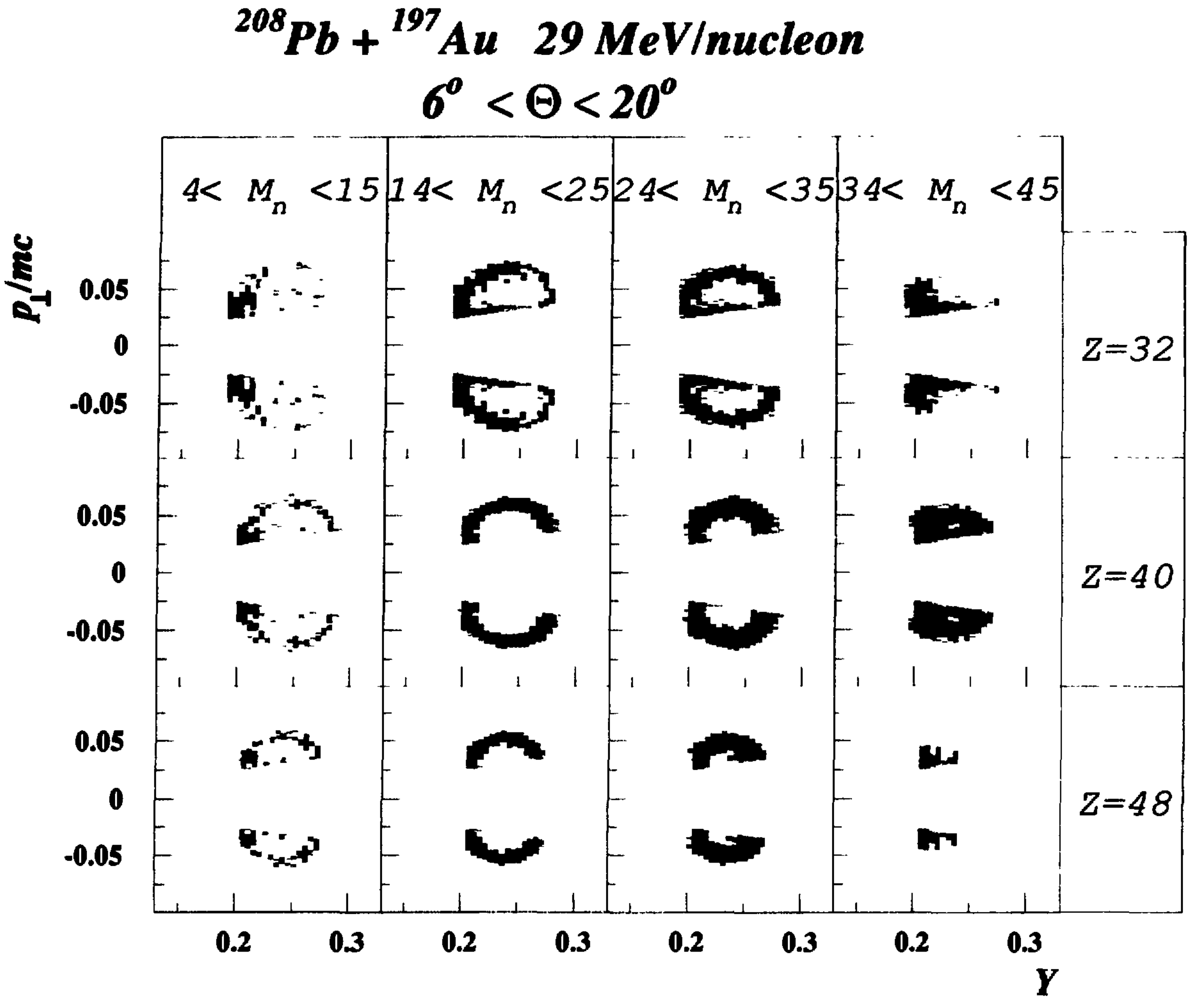
^{208}Pb + ^{197}Au 29 MeV/nucleon
6° < Θ < 20°
4< M_n <15
14< M_n <25
24< M_n <35
34< M_n <45
Z=32
Z=40
Z=48
$p_\perp/mc$
0.05
0
-0.05
0.2
0.3
Y

Fig. 1

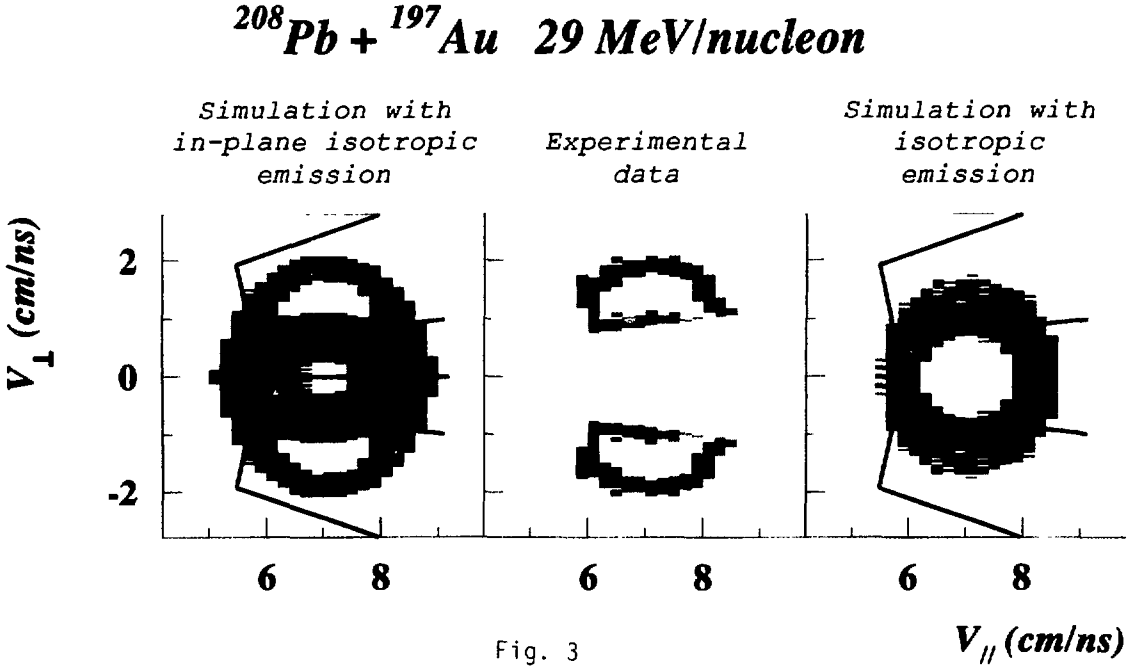
^{208}Pb + ^{197}Au 29 MeV/nucleon
Simulation with in-plane isotropic emission
Experimental data
Simulation with isotropic emission
$V_\perp$ (cm/ns)
2
0
-2
6
8
$V_{//}$ (cm/ns)

Fig. 3

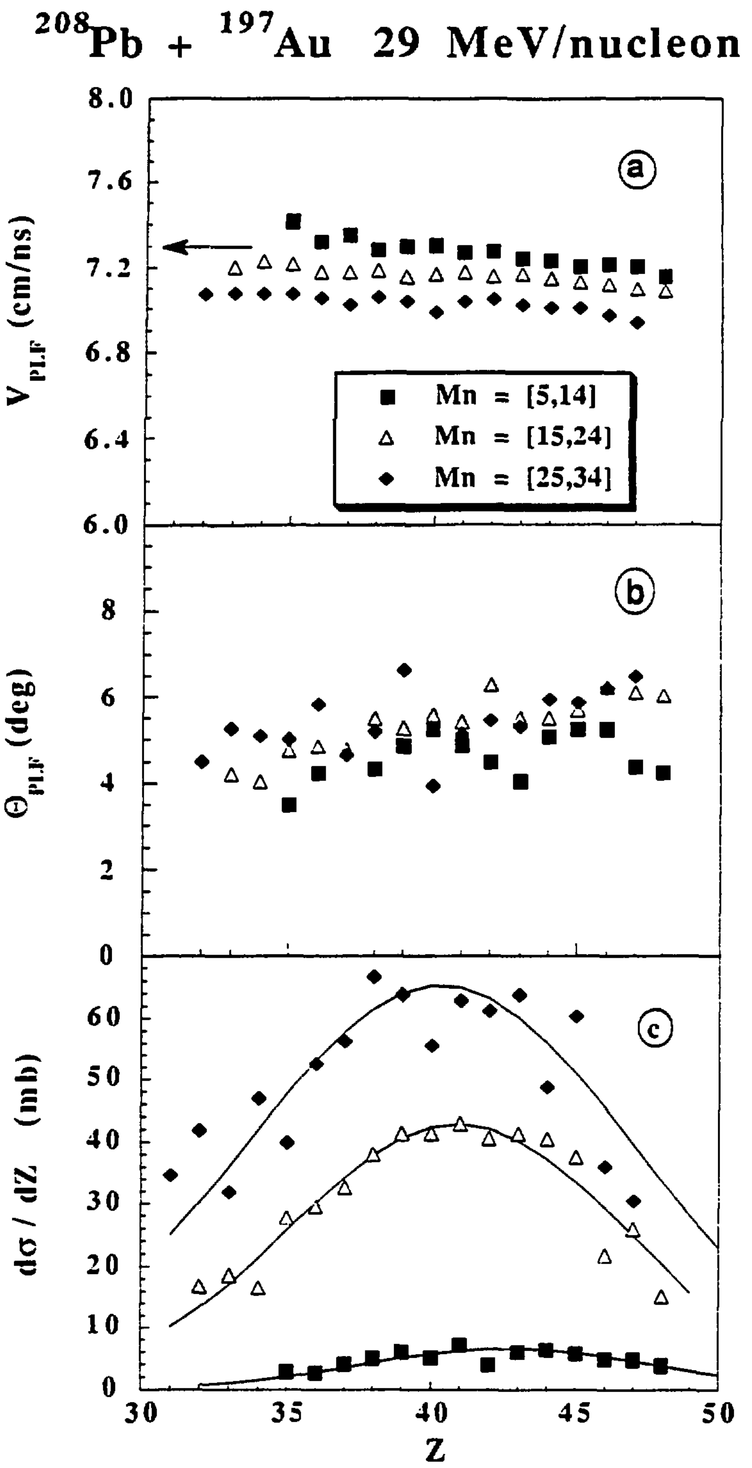
^{208}Pb + ^{197}Au 29 MeV/nucleon
a
b
c
V_{PLF} (cm/ns)
Θ_{PLF} (deg)
dσ / dZ (mb)
Z
■ Mn = [5,14]
△ Mn = [15,24]
◆ Mn = [25,34]
8.0
7.6
7.2
6.8
6.4
6.0
8
6
4
2
0
60
50
40
30
20
10
0
30
35
40
45
50

Fig. 2