A COMPREHENSIVE STUDY OF FISSION IN 24.3 MEV/NUCLEON U REACTIONS INDUCED ON C, SI, NI, AU TARGETS

E.PIASECKI1), L.PIENKOWSKI2-5), M.MUCHOROWSKA3), A.TUCHOLSKI4), T.CZOSNYKA1),
A.CHBIHI5), E.CREMA5-6), W.CZARNACKI4), GALIN5), B.GATTY7), D.GUERREAU5),
J.IWANICKI2), D.JACQUET7), U.JAHNKE8), J.JASTRZEBSKI2), M.KISIELINSKI4),
A.KORDYASZ1), M.LEWITOWICZ5), M.MORJEAN5), J.POUTHAS5)

Invited paper at the second International Symposium on
Heavy Ion Physics and its applications,
Lanzhou (China) August 29-September 1, 1995

GANIL P 95 22

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A.KORDYASZ1), M.LEWITOWICZ5), M.MORJEAN5), J.POUTHAS5)

1) Institute of Experimental Physics,Warsaw University, Hoza 69, 00-681 Warsaw, Poland
2) Heavy Ion Laboratory, Warsaw University, Banacha 4, 02-097 Warsaw, Poland
3)Warsaw University of Agriculture, Rakowiecka 26-30, Warsaw, Poland
4)Soltan Institute for Nuclear Studies, 05-400 Swiek, Poland
5) GANIL, BP5027, 14021 Caen-cedex, France
6) Instituto de Fisica, Universidad de Sao Paulo, Sao Paulo, Brazil
7) Institut de Physique Nucléaire, BP1, 91406 Orsay-cedex, France
8) Hahn Meitner Institut, Glienicker Strasse 100, 14109 Berlin, Germany

GALIN e-mail address: GALIN at FRCPN11.IN2P3.FR

ABSTRACT

Fission is a powerful tool for studying the primary reaction mechanisms in nucleus-nucleus collisions involving at least one fissionable nucleus. This is well shown when an additional information on the violence of the collision is provided by a totally independent observable such as the neutron multiplicity. The mass asymmetry in the entrance channel and the impact parameter are shown to have a decisive influence on the fate of the collision leading to either fusion or a two-body deeply inelastic reaction, analogous to what is known at lower bombarding energies. The experimental approach allows also to single out electromagnetic fission of U after interaction with Au and to provide some characteristics of such a process.

1. What can be learnt from fission in nucleus-nucleus collisions?

Since the pioneering work of Sikkeland (1962) fission has been extensively utilized in order to investigate the reaction mechanisms in heavy-ion induced collisions. Indeed some characteristics of the fission fragments can reveal the properties of the fissioning nucleus and thus provide relevant information on the reaction steps preceding fission (Viola 1989). The Z/mass distribution pattern of the fragments can reveal the amount of excitation energy of the fissioning nucleus, the total Z/mass of the two fragments: the amount of transferred matter between projectile and target, the folding angle between the fission fragments: the linear momentum transfer prior to fission, the angular distribution of the fragments: the nature of the excited states, their spin.

Although the fission process is potentially very informative, the provided information is sometimes misinterpreted. This has often been the case in experimental analysis where the linear momentum transfer has been used in order to infer excitation energies. In the literature the corresponding approach is assumed to reflect a massive transfer or an incomplete fusion (Viola 1989). It is assumed that the linear momentum is transferred towards the heavier partner through an exchange of nucleons from the lighter partner to the heavier one, with these nucleons carrying the average momentum they had initially. The deposited energy is deduced accordingly. In fact such an assumption has been verified experimentally only at rather low bombarding energy for a very asymmetric system. This has been done by using the neutron multiplicity measured in coincidence as a complementary observable of excitation energy (290 MeV Ne on U, Galin 1988). For a slightly more symmetric system (400 MeV Ar on U, Schwinn 1989) two distinct families of events are observed corresponding to fusion and deeply inelastic 2-body reactions. It is shown that the momentum transfers can be noticeably different for similar excitation energies. Clearly the momentum transfer measurements cannot be used safely to determine excitation energies. This observation prompted us to make a detailed investigation of fission as a function of the mass asymmetry in the entrance channel (Piasecki 1995).

2. Fission of U-like nuclei after interaction of a 24.3 MeV/nucleon U beam with C, Si, Ni, Au.

In order to facilitate the determination of the fragment atomic number, Z, the so called reverse kinematics is utilized, using the U nucleus as a projectile. Moreover, a great improvement was done when compared with earlier experiments (Justice 1993) by measuring event-wise the neutron multiplicity. The latter quantity provides a valuable information on deposited energy i.e. on impact parameter (Galin, Jahnke 1994).

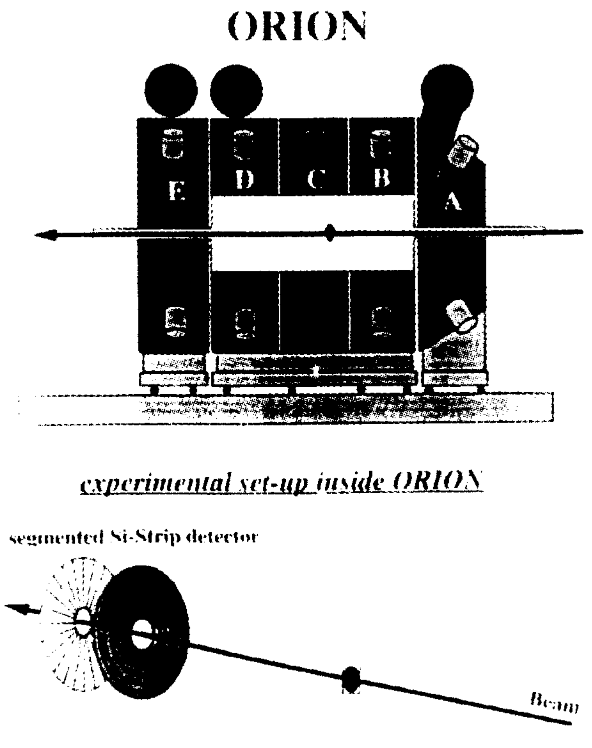


Fig.1 Layout of the experimental set-up, with the ORION neutron detector, a 4π, $4m^3$, liquid scintillator detector loaded with gadolinium and the multistrip, annular, Si detectors of the fission fragments.

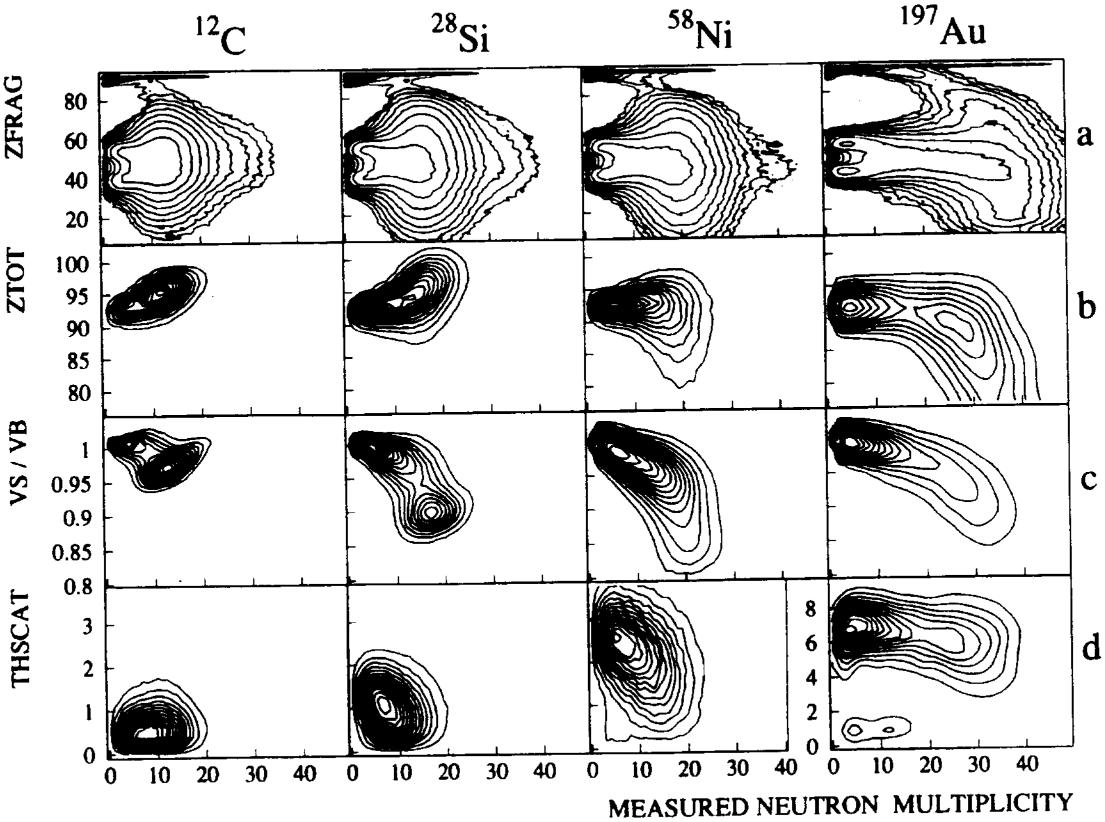


Fig.2 Distribution of events after interaction of 24.3 MeV/nucleon U with C, Si, Ni, Au as a function of the neutron multiplicity and:
-a: the charge, ZFRAG, of a nucleus as measured in single (the z scale is logarithmic)
-b: the total charge, ZTOT, of two coincident fragments
-c: the deduced velocity, VS, of the fissioning nucleus normalized tothe beam velocity, VB
-d: the deduced scattering angle, THSCAT, of the fissioning nucleus
For details see (Piasecki 1995)

The experimental set-up is sketched in Fig.1 and the details can be found elsewhere (Piaseki 1995). The emission angles of the two coincident fragments are measured using annular Si strip detectors with concentric strips for the ΔE detector and radial strips for the E detector. The atomic numbers are identified by means of the ΔE-E information. The Z and E information are used to infer the fragment mass and hence its velocity. From these quantities a kinematical reconstruction of the fissioning nucleus is possible. The total Z of the detected fragments, ZTOT, provides information on the proton flow between projectile and target in the first step of the reaction and the velocity vector of the fissioning nucleus gives information on both the scattering angle, THSCAT, and energy damping (VS/VB representing the velocity of the fissioning nucleus normalized to the beam velocity). All these quantities are measured as a function of the neutron multiplicity (Fig.2).

The upper panels in Fig.2 show the Z distributions of the forward emitted products for four different targets as they are obtained without imposing the coincidence requirement between fragments, thus showing U-like evaporation residues as well. The latter appear as bridges between pure elastic scattering (Z=92 and Mn=0) and fission fragments. It is shown that they are lighter and lighter with increasing Mn. The considered nuclei have increasing fission barriers preventing them from fissioning (Note that the horizontal line at Z=92 is unphysical, it corresponds to double events with an elastically scattered U detected in coincidence with the neutrons from an inelastic collision). It is worth mentioning that even when starting from an easily fissionable nucleus (B_f=5.7 MeV for ^{238}U) and for large energy dissipation (large Mn), fission has not a hundred per cent probability to occur.

The evolution from a doubly-humped distribution peaked at Z=40-52, as expected for low Mn (cold fission), to a single-peaked symmetric distribution at high Mn, with a sizeable broadening with increasing Mn is clearly visible for all targets in Fig.2b. A more detailed picture is provided as an exemple in Fig.3 for ZTOT=94 produced in the U+Si reaction. These well known features demonstrate the effectiveness of the neutron filter in selecting between the different types of fission following the primary nucleus-nucleus interaction. Due to the relative size of the interacting nuclei, for the lightest targets (C, Si) most of the neutrons arise from the heavy fissioning nucleus whereas for heaviest targets they come from both nuclei: projectile-like and target-like nuclei. It is interesting to note that for the Pb+Au system studied at a similar energy, fission events are only seen for Mn>5 with symmetric Z distributions (Piasecki 1991 and Pienkowski 1992). This is due to the highest fission barrier of Pb and neighbouring nuclei as compared to U.

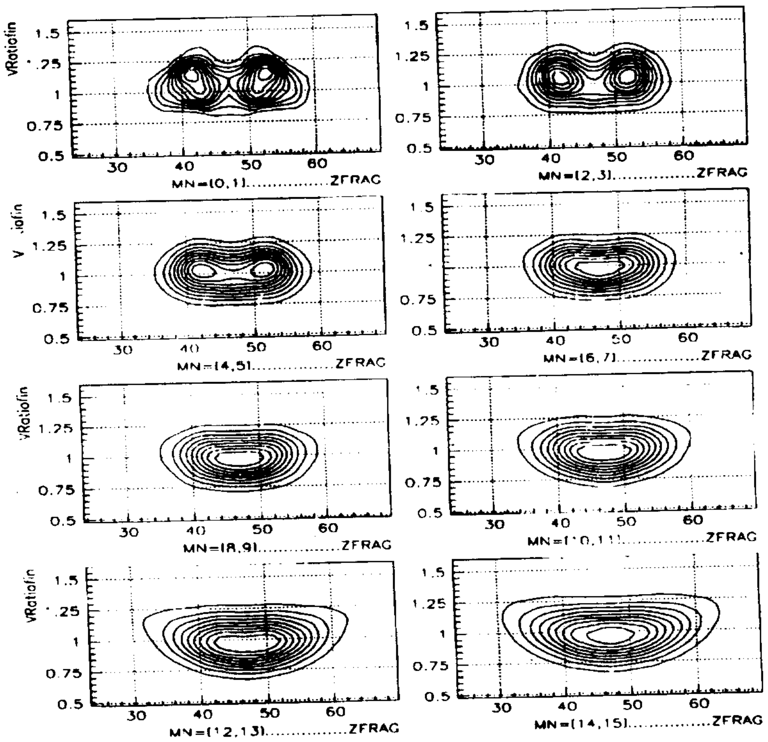
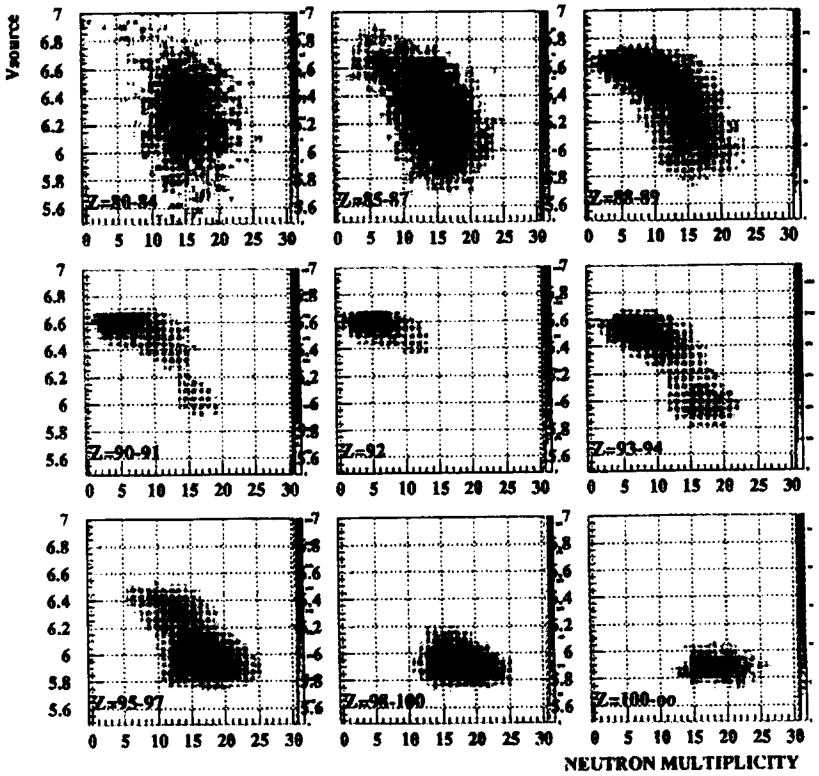
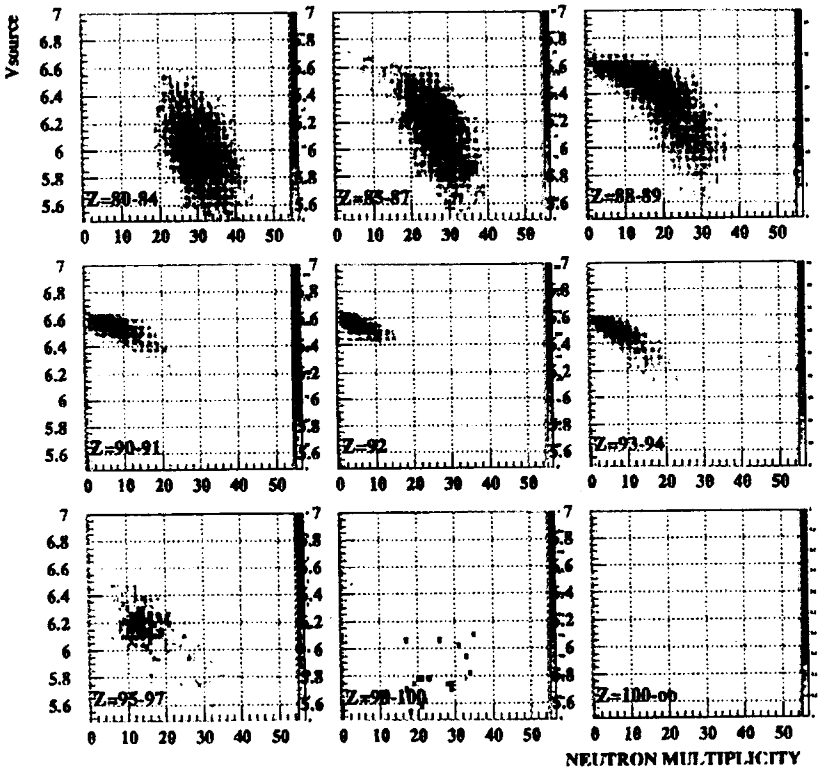


Fig.3 Fission fragment distribution as a function of their normalized kinetic energy (ordinate) and their charge, ZFRAG, for different neutron multiplicity bins, MN. The considered events are characterized by ZTOT=94 and are produced in the U+Si reaction. (unpublished data from: Piasecki, Pienkowski 1995)

Data in Fig. 2b, c, d refer to coincidence events between two fragments and are interesting in so far as the properties of the fissioning nucleus can thus be deduced. The evolution of the charge of the fissioning nucleus is shown to vary in quite opposite ways with Mn, depending on the target nature. For the lighest ones (C, Si), the more dissipative the collision, the heavier the fissioning nucleus appears to be: there is an evolution towards more and more complete fusion when Mn increases. In contrast for the Ni and Au targets there is no gain of Z on the average prior to fission. One can even see a loss for the highest Mn, consecutive to abundant charged particle evaporation or/and three-body (multi-body) partition instead of binary fission (with one or more undetected fragment(s)).



U+Si



U+Au

Fig.4: Scatter plots of fission events as a function of the velocity, Vsource, expressed in cm/ns, of the fissioning nucleus and the measured neutron multiplicity for different bins of Z: the total measured charge of the coincident fission fragments (unpublished data, Piasecki and Pienkowski 1995). The upper panels refer to U+Si and the lower ones to U+Au.

The existence of fusion-fission as a separate type of events appears readily in Fig.2c for the C and Si targets, when considering the distribution of the fission events as a function of the velocity of the fissioning nucleus (normalized to beam velocity) and Mn. The fusion-fission events appear as a distinct contribution. On the average the momentum transfer is 80% for such events in good agreement with the systematics (Viola 1989). More detailed information combining the data of Fig.2b and 2c are presented in Fig. 4 for the Si and Au targets. With the Si target, fusion-fission appears as a distinct contribution for events with a measured ZTOT ranging from 90 to 100, Mn=15-20 and for a velocity of the fissioning nucleus smaller than 6.2 cm/ns. Such a component is missing in the data from the Au target (and from Ni as well). In contrast, the remaining (second) component for the Si target looks very similar to what is shown for Au. (The only difference stems from the absolute values of Mn: for the Au target, those neutrons emitted by the target-like nuclei are also abundant leading to larger measured Mn values than observed with Si). In both cases one deals with deeply inelastic collisions: the heating of both partners proceeds through a stochastic exchange of nucleons (Quednau 1993) preceding fission.

These data indicate the persistence at rather high bombarding energy (25 MeV/nucleon) of potentiel energy effects similar to those known at 10 MeV/nucleon, close to the interaction barrier (Moretto and Schmitt 1976). It is only for rather asymmetric systems and for central collisions that the driving force in the potential energy surface is sufficient to drive the system towards fusion. For asymmetric entrance channels (U+C or U+Si), fusion is reached in central collisions and two-body deeply inelastic events in more peripheral ones. For U+Ni and U+Au, only the second type of events exist. It can also be noticed that fusion is the only way to form nuclei of Z=100 and above with sizeable cross sections. The fluctuations in Z in the deep inelastic interaction of U with Ni or Au are weak and do not permit synthesis of nuclei of Z>100 in sizeable quantity.

From the data of Fig.4 it turns out that the deduction of dissipated energy from the kinematical properties of the fissioning nuclei -using an incomplete fusion or massive transfer approach, as generally done- is uncorrect when one deals with deep inelastic processes. This is best exemplified for the Z=80-84 gate where a very broad velocity distribution of the fissioning nuclei is associated with a rather narrow and almost constant Mn distribution (Fig.4). The latter quantity provides a more direct response as far as the energy dissipation is considered.

The scattering angle (THSCAT in Fig.2d) of the fissioning nucleus offers also very valuable information on the collision dynamics as a function of Mn. Grazing collisions are selected by low Mn values and it can be checked that the most probable angles agree with the quarter point values computed for the four studied systems. The evolution of the deflection angle with impact parameter (and Mn is a good indicator of the impact parameter) is best shown for the heaviest target. Qualitatively the opposite effects of Coulomb and nuclear forces are shown to somewhat balance each other in the region of peripheral collisions whereas the attractive nuclear forces prevail at smaller impact parameters as it was found in dynamical calculations for the similar, Pb+Au, system (Bresson 1993). In absence of Mn measurements there will be no possible distinction between the very dissipative collisions and those much more peripheral, dominated by the Coulomb field and thus weakly dissipative.

3. Coulomb fission of U after interaction with Au

The above mentioned capabilities of the detection system have been exploited to investigate fission following a purely electromagnetic interaction. A detailed account of this study will be published soon (Piasecki, Pienkowski 1995) and in this contribution we present some interesting features highlighting the originality of the experimental approach.

So far, fission of a nucleus induced by the time-varying Coulomb field of another nucleus passing by, outside the range of the strong nuclear force, has been essentially investigated in two extreme conditions, either at sub-barrier energies (Oberacker 1985) or at relativistic energies (Polikanov 1994). In both cases the electromagnetic fission process occurs with cross sections larger than -or at least comparable to- the nuclear fission cross sections. This facilitates the investigation of the electromagnetic process. Such is not the case at 24 MeV/nucleon bombarding energy when pure electromagnetic fission of U in the Coulomb field of Au is expected to contribute to only the per mil or per cent of the total fission cross section. Is it possible to single out such rare events in order to study them thoroughly?

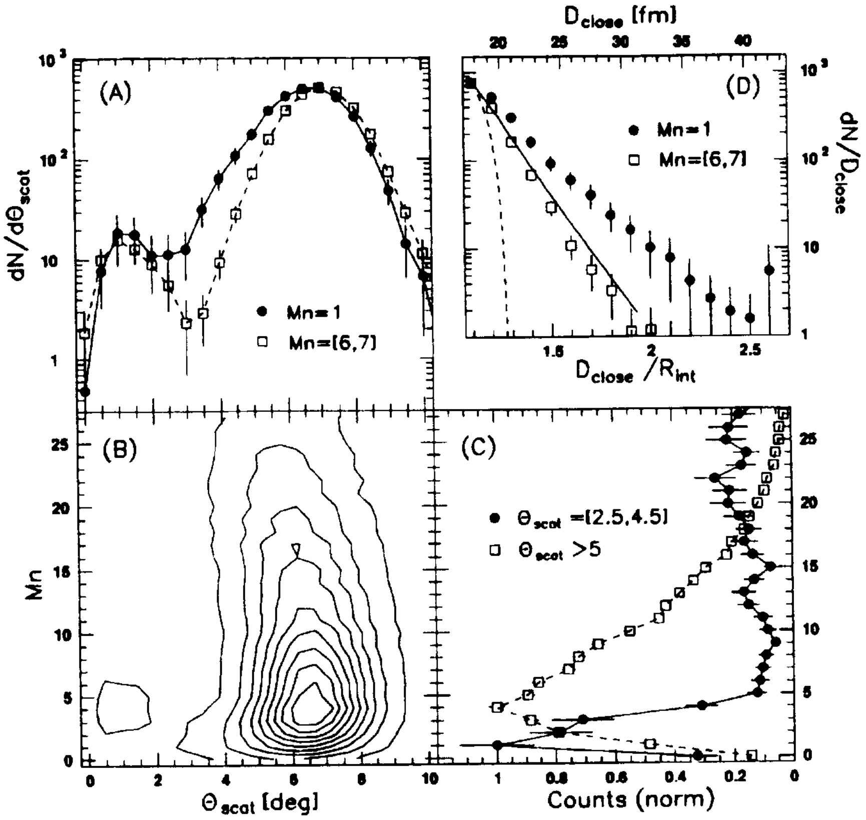


Fig.5 Lower panel left (B): contour distribution of fission events with Z=92 as a function of the measured neutron multilplicity and scattering angle Θ_{scat}, of the fissioning nucleus. Lower panel, right, (C) and upper panel, left, (A) provide normalized projections of the Mn and Θ_{scat} distributions with gates in Θ_{scat} and Mn, respectively. The spectra are arbitrarily normalized. Upper panel (D): normalized distributions of events as a function of the distance of closest approach, as measured (symbols) and after correction for detection resolution (lines). The dashed line refers to Mn=6-7 and the solid line to Mn=1. All distributions are arbitrarily normalized.

The first necessary condition to be applied for selecting such events is given by ZTOT=92. Indeed the expected excitation energy in an electromagnetic process is too low (13 MeV and 10 MeV for excitation of the GDR and GQR respectively) to allow for charged particle evaporation prior to fission: at these energies only neutron evaporation is possible (Lott 1993). This necessary condition is not sufficient since it does not prevent from selecting nuclear reactions with a proton exchanged back and forth, or any kind of neutron transfer preceding fission. The only way to minimize the occurence of such contaminating nuclear processes is to select very distant collisions such that the overlap of the wave functions of the nucleons from the two partners tends to zero. This is actually what is done in sub-barrier studies: The bombarding energy is chosen low enough for the closest distance of approach between the nuclei to be large enough to forbid nuclear interaction. This has led to the concept of a "safe distance of approach", a distance for which the nuclear contamination is considered as negligeable. The same concept can be used at energies above the barrier provided one is able to determine event-wise, the distance of closest approach. Both scattering angle and neutron multiplicity information have been used for such a purpose in the present case.

It is shown in the contour level plot of Fig. 5 that the requirement of ZTOT=92 is by no means very selective. As shown previously this is due to deeply inelastic collisions. The selection of U as the fissioning nucleus can lead to almost any type of collision with excitation energies ranging from a few MeV to close to 1 GeV. The potential candidates for electromagnetic fission appear as a "verruca" in the lower left corner of the contour plot at small scattering angle (large closest distance of approach) and low neutron multiplicity (low excitation energy) as shown in Fig.5. This is singled out by projections onto both axis: Mn and scattering angle. It is shown that when selecting two different angular ranges, Θ_{scat}=2.5-4.5 degrees (events with a lower Θ_{scat} are due to contamination of the Au target with light materials) and $\Theta_{scat}>5$ degrees, the neutron multiplicity spectra are quite different (Fig.5A-5C). In the latter case where nuclear fission is expected to be dominant, the distribution is very broad, indicating all kinds of excitation. In contrast a narrow peak is seen on top of some background for distant collisions (small Θ_{scat}). It is also shown on the Θ_{scat} spectra for two distinct ranges of Mn that the distributions are notably different with an excess of events with low Mn at small angle which can be attributed to electromagnetic fission. The selection in both Θ_{scat} (from 2.5 to 4.5 degrees) and Mn (from 0 to 3) allows isolation of the events of interest. It is worth stressing that without the Mn information a very strong contamination by nuclear events would have been unavoidable, making a detailed study of electromagnetic fission impossible.

Are all selected events pure Coulomb fission events? What is the contamination level due to nuclear fission? A detailed analysis (Piasecki and Pienkowski 1995) taking into account all experimental sources of angular broadening (finite size of the strips and of the beam) shows that the considered events correspond to closest distances of approach exceding 22 fm and reaching values up to 30 fm (Fig.6D). For nuclear fission events with a slightly larger excitation energy (Mn=6-7) a very abrupt fall off is seen for 20 fm as the closest distance of approach. The contamination of Coulomb by nuclear fission is thus expected to be weak in the present data as they are selected. This also means that part of all Coulomb fission events are rejected because of the drastic criteria which need to be imposed because the finite resolution of the detection system.

In terms of distance of closest distance of approach the present data are very similar to the ones obtained in sub-barrier experiments (Himmele 1982). However the excitation mechanisms is thought to be quite different due to the differences in interaction time. In the sub-barrier case this time is long enough to allow multi-step excitation of vibrational-rotational states. Coulex calculations (Piasecki and Pienkowski 1995) show that at the present bombarding energy only rather low spin states can be reached with cross sections of about 1 mb for the range of scattering angles considered experimentally. On the other hand the virtual photon approach (Bertulani and Bauer 1985) currently used to interpret the data at relativistic energies leads to rather low cross sections at 24 MeV/nucleon (Polikanov 1994). This is confirmed by rough estimates (Volpe and Chomaz 1995). It is shown that only the low energy tail of the Giant Resonance modes is excited with a sizeable probability and that the cross section in the domain explored experimentally should be comprised between 1 and 10 mb. The experimental cross sections, not estimated with a better accuracy, do not disagree with such figures.

Detailed investigation of the Z distribution of the fission fragments after nuclear and Coulomb fission and comparison with photofission data (Pommé 1994) are in progress (Piasecki and Pienkowski 1995). The neutron multiplicity information is shown to provide very sensitive constraints in this study.

4. Summary and outlook

Fission has been shown to be a very informative process in the study of the nucleus-nucleus reaction mechanisms. The influences of mass asymmetry in the entrance channel and impact parameter have been investigated in U+C, Si, Ni, Au reactions. The conditions for fusion are understood in terms of static effects determined by the potential energy surface of the system as a function of mass asymmetry and angular momentum. This is reminiscent of what has been learnt at lower bombarding energy, close to the interaction barrier.

The present experimental approach combining detailed characterization of the fission fragments together with an independent measurement of the dissipated energy, utilizing the neutron multiplicity observable, allows to single out Coulomb fission events which represent only 10^{-3} to 10^{-2} of all measured fission events. This technique can still be improved in order to make possible a detailed investigation of this process at energies several times higher than the barrier where the data are very scarce. It would be of great interest to investigate the dependence of such a phenomenon with the Z of the interacting nucleus (dependences in Z^6 and Z^2 for subbarier and relativistic energies, respectively), and with the nuclear structure of the fissioning nucleus.

Acknowledgements: The authors are indebted to IN2P3-CNRS, the Komitet Badan Naukowych and the Polish Academy of Sciences for financial support. They express their thanks to B.Lott, L.Moretto, Ph.Chomaz and C.Volpe for useful discussions.

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