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Abstract: Coulomb fission of ^{238}U has been studied in the interaction of a 24.3 MeV/nucleon U beam with a Au target. A novel experimental approach is followed, allowing to isolate the Coulomb fission from the nuclear fission on an event by event basis. The Z distribution of the fragments is studied for both fission processes.

The term of Coulomb fission (CF) is used here with the meaning of a fission of a nucleus induced by the time-varying Coulomb field of another nucleus passing by outside the range of the strong nuclear force1). Its interest lies, among others, in the direct coupling of the electromagnetic field to collective degrees of freedom, which can result in a time scale much faster than in fission induced by the nuclear interaction. However experimental data about this phenomenon are very scarce. The main difficulty in investigating such a process stems from the presence of nuclear induced fission which can be easily confused with electromagnetic induced fission. In order to overcome this major problem, two distinct paths have been followed so far.

At the end of the seventies, when very heavy-ion beams became available, sub-Coulomb induced fission reactions were first investigated. By lowering the beam energy with respect to the Coulomb barrier by about 15%, the nuclear fission cross section becomes small as compared to the Coulomb one. However, most of the experiments were inconclusive in the absence of proof that the fission barrier was not overcome following a nucleon transfer reaction[2-4]. The less ambiguous observation of Coulomb fission was made by requiring a coincidence with the back-scattered partner[5-6]. Even in such a case, the distinction between inelastic Coulomb and nuclear excitation was not fully possible and the conclusion of Coulomb dominance in the observed data was reached only by comparison with theory. The latter predicted the observed strong cross section dependence on charge number of the interacting nuclei. The obtained data were limited essentially to cross sections, which for fission of ^{232}Th, ^{238}U and ^{248}Cm induced by W projectiles were in the 1-10 mb range.

The second experimental approach of CF has been developed more recently with very heavy ion beams at relativistic energies. At such energies, the giant resonance modes are excited with large cross sections, making Coulomb induced fission a process of a weight comparable to or even larger than nuclear fission[7]. But so far in these studies, event by event differentiation between nuclear and Coulomb fission has not been performed and only cross section measurements have been carried out. Cross sections of about 500 mb have been deduced experimentally for Coulomb fission of U in the U+U interaction at 120 MeV/nucleon[8] and about 2 b in the Pb+U interaction at 1 GeV/nucleon[9] in good agreement with model calculations.

In the present letter we report the results of the first electronic counter experiment aimed at measuring the fragment Z distribution for Coulomb fission of ^{238}U. The experiment has been performed at GANIL with a ^{238}U beam impinging on a Au target. The pattern of the fragment distribution bears the fingerprints of the states which are excited prior to CF.

The experiment is part of a more extensive program carried out on C, Si, Ni and Au targets and an account of the nuclear fission characteristics has been already given elsewhere[13]. In the present letter we concentrate on CF which was observed in the U+Au interaction where the Coulomb field is the strongest. The fission fragments of the projectile-like nuclei were detected in coincidence by means of an annular telescope centered on the beam axis. The outer diameter of the telescope was 3". An inner hole of 0.5" in diameter enabled the beam passing through. The telescope was made of two silicon detectors with thicknesses of 150μm and 500μm respectively. For localization of the fragments in polar angle Θ, the front detector was subdivided into two halves consisting in 16 annular strips each. The rear detector was made of 32 radial strips for azimuthal localisation, Φ. The distance between target and the front detector was 70 mm. The identification in Z based on the E-ΔE information has been checked *a posteriori* considering the characteristic pattern of the fission fragment Z distribution for cold fission of U. The RMS charge resolution was found equal to 0.4 charge unit at the level of Z=40 but deteriorated slowly for higher Z's. The Z calibration of the E-ΔE matrix for the heavier fission fragments was performed by using the coincidence with corresponding light partners in low neutron multiplicity events (to be discussed thereafter), which were assumed to correspond to fission of a ZTOT=92 nucleus. Due to the limited acceptance of the telescope -because of its central hole- events with fission fragments emitted parallely to the beam axis were lost. The detector efficiency as a function of all relevant kinematical variables has been calculated by Monte-Carlo simulations and taken into account during the data analysis.

The scattering chamber housing the telescope is immersed in a high efficiency 4π-neutron detector the read out of which has been trigerred by the detected fission fragments. The coincident number of neutrons accompanying each fission event is crucial for the present experiment. It allows characterizing event by event with the total dissipated energy[14]. As will be shown later on, it is eventually the ORION II neutron detector, a $4m^3$ tank of liquid scintillator loaded with gadolinium, that permits the selection of the fission events compatible with a Coulomb origin. The neutron detection efficiency depends on the neutron velocity. For neutrons with the beam velocity it is estimated to be close to 50%[15]. We exploit the fact that the detector is divided into five independent sectors and in the data analysis we take into account the forward part of the detector (3 sectors) where the neutrons of interest (coming from the projectile-like nucleus) are focussed. Doing so, the registration of both the neutrons issued from the target-like nucleus and the background is minimized.

The angular information from the silicon detectors was used along with the kinetic energies to determine the velocity vectors of the coincident fragments and then to reconstruct the velocity vector of the fissioning nucleus. For this purpose, the masses of the fragments were calculated by interpolating between (238/92)*Z for "cold" events (low neutron multiplicity) and the β-stability line for the "hot" ones.

The expected excitation energies resulting from virtual photon absorption is modest at the chosen beam energy (at most 13 MeV considering excitation of the giant dipole or quadrupole resonance modes). Assuming the damping of these modes, the statistical evaporation model tells that charged particle evaporation either prior- or post-scission is very unlikely and thus the charge of U has to be recovered in the fragments. The population of the fissioning nuclei with ZTOT=92, as a function of their scattering angle in the laboratory system and associated measured neutron multiplicity, is given in Fig.1. It is seen that a large fraction of events originate from nuclear fission characterized by a large energy dissipation (large neutron multiplicities).

Distinction of the Coulomb fission can be done by exploiting two leading properties for such a process: large distance of closest approach between projectile and target and modest excitation energies. An excess of events, showing up as a tail, can be seen in the contour plot of Fig.1B for scattering angles close to 4 degrees and detected neutron multiplicities, Mn, less than 4 units. Note that the separated island observed with $\Theta_{scat}<2$ degrees must originate from reactions on light impurities deposited on the target: indeed the corresponding fission events resemble very much those observed with a C target[13]. This similarity concerns distributions of ZTOT, Mn, $\Theta_{scat}<2$ and the correlations between them. One can see that a mean deflection angle smaller than $\Theta_{grazing}$ can be obtained both for very peripheral collisions (low Mn) and for very dissipative ones. In the latter case bending of the deflection function towards small values is caused by the attractive nuclear field. This shows the invaluable role played by an efficient 4π neutron detector in distinguishing between the two situations. One can note that a light charged particle (lcp) detector used instead of the neutron one would not have been sufficient in this respect because of the high excitation energy threshold for lcp evaporation from heavy nuclei.

The deflection angle can be related to the closest distance of approach using a classical approximation. This is illustrated in Fig.1D for fission events characterized by different neutron multiplicities. These distributions have then been corrected for the finite size of the beam and of the strips responsible of the angular broadening (with a RMS of 0.9 degrees as estimated from Monte-Carlo simulations). Normalization of these distances to the strong "interaction distance"[16], R_{int}, shows that whereas the "warm" events (Mn=6-7) are restricted to close encounters, the cold ones (Mn=1) extend to distances as large as twice R_{int}. At such distances the contamination of pure Coulomb interaction by neutron transfer is negligeable as shown in ref.[17] and after taking into account the differences in bombarding energies[18].

In order to select the CF events and avoid a sizeable admixture of nuclear fission (NF) ones, limits in Θ_{scat} and Mn were set at 2.5-4.5 degrees and 0-3 neutrons, respectively. The deflection angle of 4.5 degrees corresponds to a closest distance of approach of 25 fm to be compared with 16 fm the distance for the touching nuclei. The effects of the selections in Θ_{scat} and Mn are best seen in the projections of Fig.1A-1C. The angular distributions corresponding to Mn=1 (i.e. for both Coulomb and nuclear fission) and to Mn=6-7 (i.e. corresponding essentially to nuclear fission) exibit a marked difference below 4.5 degrees where Coulomb fission is expected to be strongly dominating. Also, the neutron multiplicity distributions shown for Θ_{scat}=2.5-4.5 degrees and above 5 degrees have very different patterns. The latter is quite broad, typical for a nuclear interaction, whereas the former exhibits a pronounced maximum at low neutron multiplicity as expected for fission following a Coulomb interaction. After taking into account the neutron detection efficiency the neutron distribution appears only slightly wider than what has been measured for fission at an energy close to the barrier[19]. This means that the excitation energy of nuclei fissioning after Coulomb interaction has some finite but small width.

Estimates of the excitation energies which are populated in the present experiment can be tempted using recent photofission data for ^{238}U[20]. In the latter it is shown that the Z distribution of the fragments remains essentially unchanged for excitation energies up to 2 MeV above the fission barrier (Bf=5.7 MeV) with the manifestation of a pronounced even-odd staggering and a pronounced maximum at Z=40. For excitation energies larger than 9.7 MeV the even-odd staggering is washed out and the maximum of the distribution shifts from Z=40 to Z=39. The NF data are compared to the photofission data in Fig. 2D-2G after the latter have been folded with our detection resolution. The initial even-odd effects hardly survive our fission detection and no strong argument can be made in the comparison with the U+Au data with respect to this observable. However the general change of shape of the distributions with increasing excitation energy or increasing Mn is noteworthy. A reasonable agreement is found when comparing the NF data with the photofission ones provided a low excitation energy ($E^*<8.4$ MeV) is selected for Mn=1 and $E^*=9.7$ MeV for Mn=2. Evolution of the distribution illustrates the capability of the neutron filter to select the initial temperature of the fissioning nucleus. Also it is seen (Fig.2D-2G) that the peak-to-valley ratio of the distributions (in fact we show only half of the symmetric distibutions, thus the valley corresponds to Z=46) depends strongly upon the selected neutron multiplicity, i.e. the excitation energy of the fissioning nucleus. This is a known feature of fission in general[21)].

As far as we know this is the first time that Coulomb induced fission can be studied event-wise in a counter experiment implying two heavy partners above the Coulomb barrier. The cold character of CF in general is demonstrated by the high peak-to-valley ratio observed for Mn=1-3 (Fig.2A-2C). The increase of excitation energy with Mn is suggested by the evolution of the shape of the Z distributions and by the shift of their maxima from Z=40 to Z=38. However better statistics would be required in order to see whether CF Z distributions differ really from the NF ones for the same Mn. One possible reason for such a difference might be the mass dependence of fragment angular distributions observed in (e,e'f), (γ, f) and (n,f) reactions and interpreted in the frame of the multi-modal neck-rupture model[22-24)]. Comparing the present data with these of ref. 20, one should keep in mind that the former have been taken at polar angles comprised between 70 and 140 degrees in the center of mass system whereas the photofission[20)] data are integrated over all angles. Further work is required in order to gain sensitivity in Z identification and better statistics.

Two approaches have been followed so far in order to interpret CF data in two distinct energy regimes. For subbarier head-on collisions, the numerical simulations of Coulomb excitation of the known excited states have been performed using the known or estimated E2 matrix elements[1, 25-26)]. For collisions at relativistic energies, extensions of the Weizsäcker-Williams[10)] equivalent phonon model has been worked out by Alder-Winther[11)] and later, put in the context of virtual phonons by Bertulani and Baur[12)]. Since the energy of the present experiment is intermediate, the two approaches are considered.

For Coulex calculations the GOSIA computer code[27)] is used with spectroscopic data from the NNDC data base[28)]. It appears that in contrast to CF proceeding after sub-Coulomb head-on collisions, in the present case only low spin levels (2-6h) are excited. This comes from quite different excitation mechanisms, when similar closest distances are reached at very low or high velocities. In the former case the long interaction time suffices for the multistep excitation of the strongly coupled collective yrast band levels, followed by the cross-band excitation of the multiphonon collective bands[1, 25-26), with appreciable spins of 16-24h, lying 2-4 MeV above the fission barrier. The experimental results of Habs et al.29) tend to confirm this scenario, however the level of "contamination" of these data by nuclear fission is difficult to estimate. In the present case, because of the short interaction time, only direct excitation of lower spin levels is apparently possible with energy most probably very close to the fission barrier (5.7 MeV for ^{238}U). The theoretical integrated cross section for Coulomb excitation of the order of one 1 mb is found for scattering angles from 2.5 to 4.5 degrees. The estimated cross section should be multiplied by the number of collective states in the considered region (probably less than 10). However, the lack of knowledge of the electromagnetic structure of ^{238}U beyond the yrast band does not allow a precise estimate.

At relativistic energies, the virtual phonon approach gives rise to large cross sections via the GDR (centered at 13 MeV)30) and to a lesser extent via the GQR (centered at 10 MeV)8). The above discussed experimental indications of rather low excitation energy suggested that the giant resonances are only weakly excited probably because of the adiabatic cut-off factor12) caused by the low bombarding energy and large selected impact parameters. This has been confirmed by rough calculations31) showing that only the low energy tail of the resonance is excited with sizeable probability and that the cross section in the explored angular domain (i.e. impact parameter range) should be of the order to 1-10 mb. The experimental data do not allow for a precise determination of the cross section, however the estimated one is in reasonable agreement with the calculated ones.

In summary, a first attempt has been successful in studying, event by event, Coulomb fission of ^{238}U in 24.3MeV/nucleon U+Au interactions using an original experimental approach. The kinematical reconstruction of the scattering angle of the fissioning nucleus provides an information connected to the closest distance of approach, which, added to the associated neutron multiplicity allows a selection of Coulomb-like fission events. The latter are characterized by low neutron multiplicities and Z distributions indicative of fission with excitation energies close to the fission barrier. This is a clear indication that the Coulomb fission events isolated in the present experiment follow the excitation of low-lying states. The way has been paved for further investigations with an improved experimental set-up (better Z resolution and more strips on the annular detectors allowing a better accuracy in angular measurements). Event-wise selection of deflection angles could enable CF studies of nuclei with different spins. A better coverage of the phase space would provide more complete data on angular distributions. Finally the influence of the target Z on the Coulomb fission probability could also be investigated. According to calculations the direct excitation of low-spin levels should be much less target charge number dependent than in sub-barrier head-on collisions.

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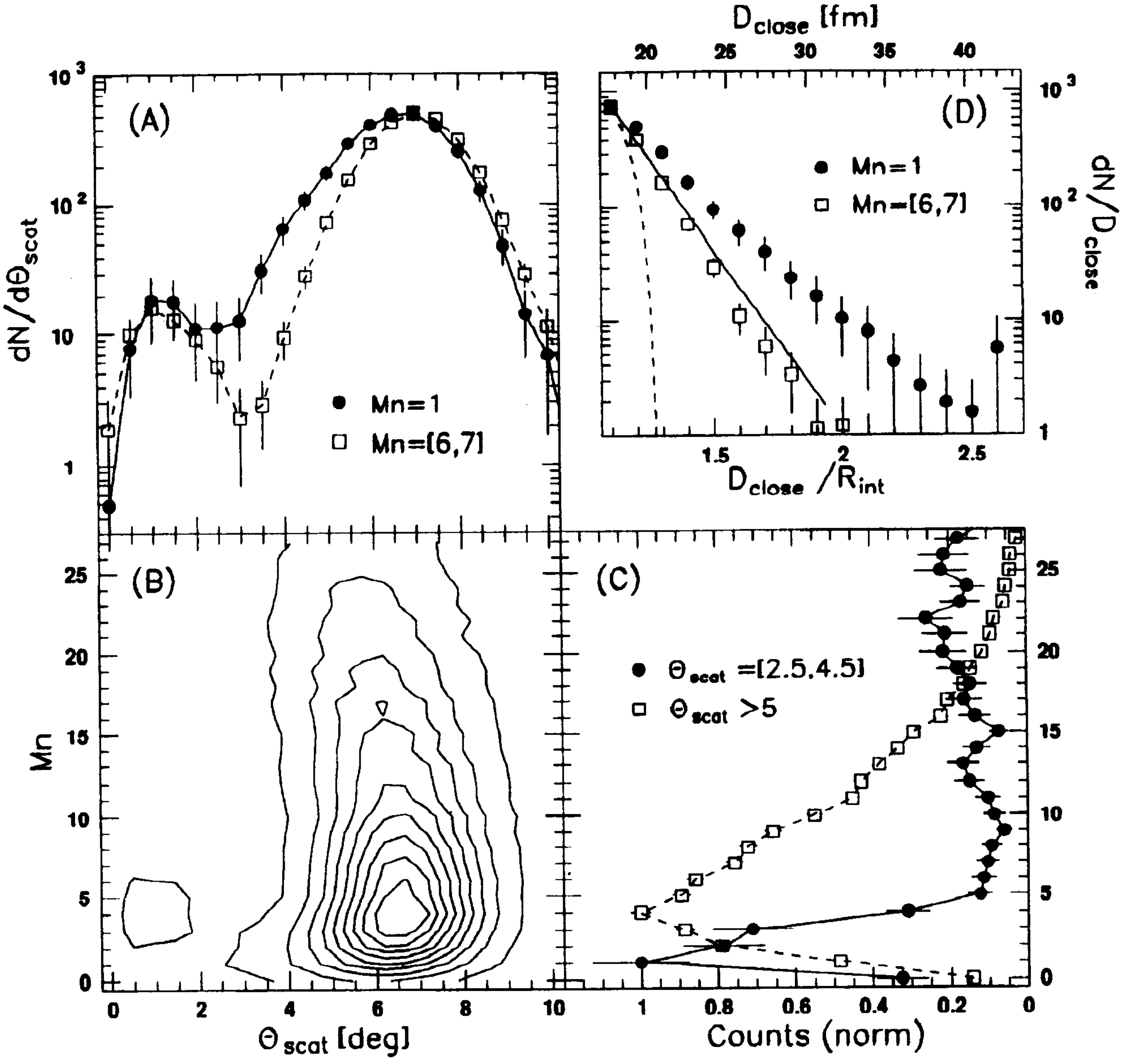

Fig.1 Lower panel, left (B): Contour distribution of fission events with Z=92 as a function of the measured neutron multiplicity, Mn, and the scattering angle, Θscat, of the fissioning nucleus. The successive levels are given in a linear scale.

Lower panel, right (C) and upper panel, left (A) are projections of the distributions with gates in Mn and Θscat respectively as given in the figures. THey are arbitrarily normalized for sake of comparison.

Upper panel, right (D): distribution of events as a function of the distance of closest approach, D close, as measured (symbols) and as corrected for the detection resolution (lines). The dashed line refers to Mn=6-7 and the solid line to Mn=1. All distributions are arbitrarily normalized. For details see text.

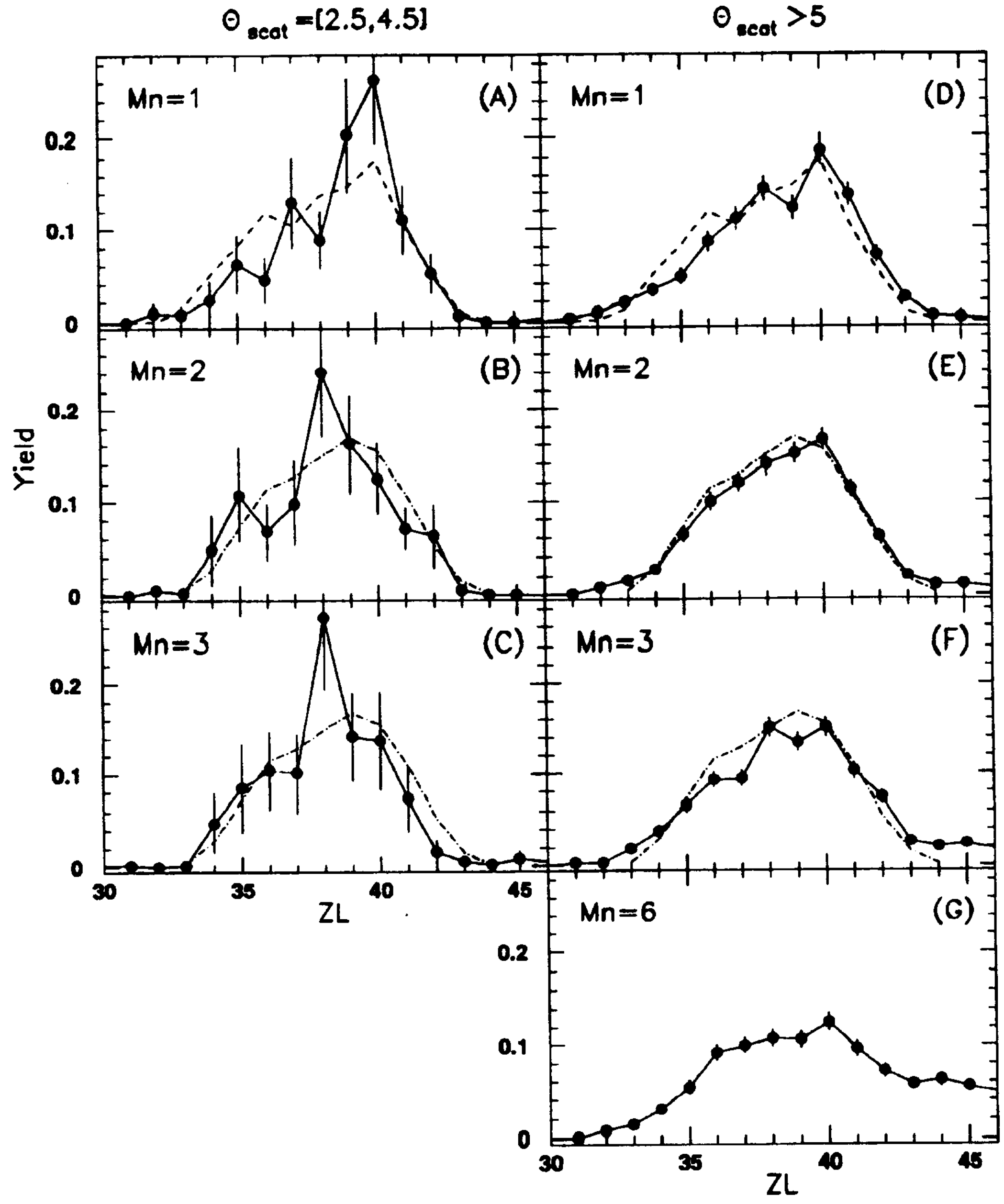

Fig.2 Left panels: Coulomb fission; Rights panels: nuclear fission. The experimental data are shown by dots whereas the lines represent photofission data[20)] folded by our fission fragment detector resolution (dashed lines: data for <E*> <8.4 MeV; dotted-dashed lines: data for <E*>= 9.7 MeV)