# Low-energy fission studies of neutron-deficient projectile fragments of $^{238}$U

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Abstract:
Low-energy fission of neutron-deficient actinium, thorium, protactinium and uranium isotopes has been investigated using a new experimental technique. The isotopes were produced as secondary beams by projectile fragmentation from a 950 A MeV $^{238}$U primary beam. Their fission was induced by electromagnetic excitation and nuclear reactions in a lead and in a plastic target. The transition from symmetric to asymmetric fission is shown to take place around N = 138.

Previous studies on low-energy fission of many different nuclear species have revealed a large variety of interesting phenomena. Most importantly, they have demonstrated the influence of nuclear shell structure on the dynamics of cold nuclear matter on its evolution towards fission. However, due to technical constraints, systematic investigations have been restricted to a limited number of nuclei. The most comprehensive studies have been performed for spontaneously fissioning nuclei [1], generally produced by heavy-ion fusion reactions. In lighter nuclei which do not fission spontaneously, excited states near the fission barrier have to be populated if low-energy fission is to be studied. The techniques used so far, i.e. neutron capture [2], photon absorption (see e.g. refs. [3,4]) and transfer or fusion reactions with light charged particles [5,6] rely on stable or long-lived target isotopes in the immediate neighbourhood of the isotope to be studied.

We report on a new technique which gives access to an extended region of neutron-deficient isotopes. These isotopes are produced by projectile fragmentation of a relativistic $^{238}U$ beam, and their excited states above the fission barrier are populated by Coulomb excitation. In a first experiment, the feasibility of this method could be demonstrated by measuring the fission-fragment nuclear-charge distributions for a series of isotopes. Results on the production cross sections of the projectile fragments which have also been studied will be reported elsewhere [7].

The GSI fragment separator [8] was used to produce secondary beams of neutron-deficient isotopes between actinium and uranium by the fragmentation of a 950 A MeV beam of $^{238}U$ in a 1.0 g/cm$^2$ copper target. The separator was operated as a momentum-loss achromat [9], using an intermediate aluminum degrader of about 4.4 g/cm$^2$. Up to seven isotopes could simultaneously be investigated in one setting of the separator. Ambiguities in the isotope separation due to the appearance of incompletely stripped ions could be avoided by measuring the time-of-flight in the second half of the separator and the energy loss in an ionisation chamber at the exit. A mass resolution of $A/\Delta A \approx 400$ (FWHM) has been achieved. The experimental equipment which is used to separate and identify the secondary beams is described in more detail in ref. [10].

The experimental setup for the present fission study is schematically shown in figure 1. At the exit of the separator, the secondary beams traversed a secondary target where fission was induced either by electromagnetic excitation or by nuclear reactions. The secondary target consisted of seven lead foils with a thickness of 0.61 g/cm$^2$ each, mounted in a vessel filled with an argon (90%) - methan (10%) mixture. By applying appropriate voltages to the foils, this 'active' target acts as a subdivided ionisation chamber, allowing to determine the foil in which a fission took place. This information was used to determine the energy dependence of the fission process and to discriminate against fission events induced in other layers of matter in front of the lead target and behind. The nuclear charges of the fission products were determined by separately measuring the energy-loss signals of both fission fragments in another ionisation chamber behind the secondary target. Due to the velocity spread induced by the fission process, the nuclear-charge resolution was limited to 1.3 charge units (standard deviation). Finally, the fission fragments were redundantly registered by two scintillation detectors in order to improve the precision on the measured fission cross sections.

The electromagnetic excitation is expected to predominantly populate the electric dipole resonance. The electromagnetic fission of $^{238}$U may be estimated from the calculated equivalent-photon spectrum of E1 radiation [11], using the cut-off against nuclear reactions as given in ref. [12], and the measured photofission cross section from ref. [3]. The calculated excitation-energy

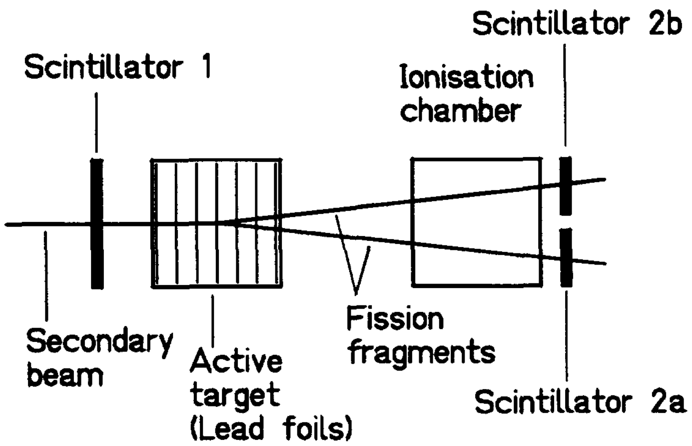


Fig. 1: Schematic drawing of the experimental setup to study the fission of secondary beams behind the fragment separator.

distribution is centered around 12 MeV with a FWHM of about 10 MeV. Therefore, mainly first- and second-chance fission occurs. The cross section for electromagnetic fission is estimated to be about 1.0 b. In addition, nuclear reactions produce prefragments, the excitation energies of which extend to much higher values [13]. They provide a contribution of high-energy fission from a variety of different nuclei.

Triggering on fission events that have occured in the scintillator 1 as a $C_9H_{10}$ secondary target, fission almost exclusively induced by nuclear reactions has been measured, too. Figure 2 demonstrates that the charge distributions of $^{238}U$ fission fragments stemming from different target materials differ considerably from each other. While the scintillator target produces a single-humped distribution, the double-humped distribution produced in the lead target indicates the presence of mass-asymmetric fission events from low-energy fission. The fact that the two target materials were traversed with different energies

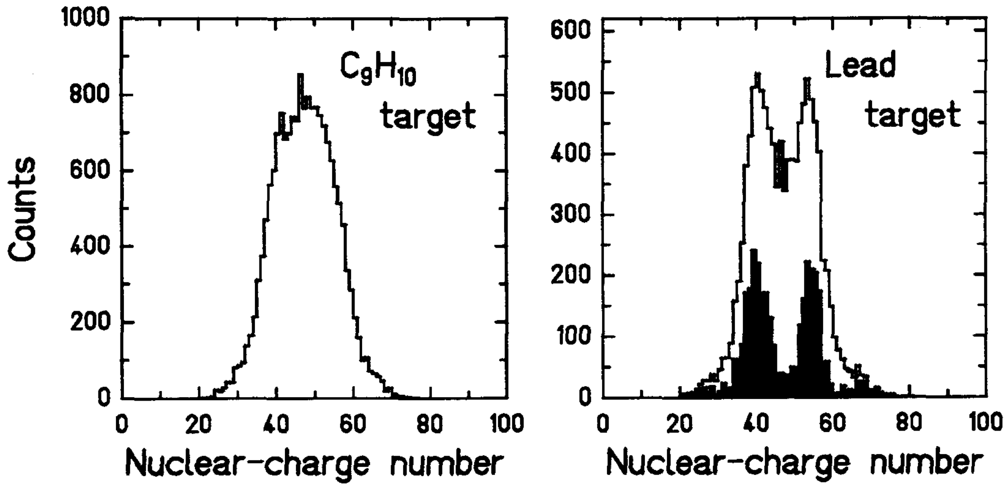


Fig. 2: Fission-fragment charge distributions of a $^{238}U$ beam measured after the passage through different targets. Left part: Fission induced in a $C_9H_{10}$ target at energies between 510 and 450 A MeV. Right part: Fission in a 3.66 g/cm$^2$ lead target at energies between 410 and 150 A MeV. The lower spectrum in the right part shows the result of an attempt to extract the charge distribution of the electromagnetic contribution (see text). Note that the abscissa was determined from the ratio of the square root of the energy-loss signals of the two fission fragments as $Z_1/(Z_1+Z_2) \times 92$. It coincides with the nuclear charge of the fission fragments only for fission of uranium isotopes.

(see figure 2) is expected to be of minor importance, since no energy depencence was found for the charge distributions from the different lead foils within the experimental uncertainties.

By registering the two fission fragments separately, fission events appeared clearly separated from other reaction channels, e.g. multifragmentation. The occurence of fission was defined by requiring the conditions

$$0.25 < Z_1 / (Z_1+Z_2) < 0.75 \quad \text{and } Z_1 + Z_2 > 50$$

on the nuclear charge numbers $Z_1$ and $Z_2$ of the two fission fragments. The total fission cross section of $^{238}U$ projectiles in the lead target at about 300 A MeV was measured to be (3.4 $\pm$ 0.3) b. This value is considerably larger than that determined by Greiner et al. [14] at 900 A MeV who obtained (2.73 $\pm$ 0.2) b. The pure electromagnetic fission component in the lead target has been extracted by subtracting the fission-fragment charge distribution induced by the scintillator target from the one induced by the lead target, using the appropriate weights determined from the total fission cross section of 3.4 b and the above-mentioned calculated electromagnetic part of 1.0 b. In this procedure we assume that the shape of the Z distribution of nuclear fission in the lead target is the same as the Z distribution of all fission events occuring in the scintillator target. Small contributions from fission events in air, in the counting gas and other layers of matter have been estimated and subtracted. Figure 2 demonstrates that this procedure leads to a charge distribution with a considerably more pronounced dip for symmetric charge splits. Within the uncertainty of the estimate, this distribution agrees with the result of electron-induced fission of $^{238}U$ at an excitation energy of 12 MeV [4] which shows a peak-to-valley ratio of about 7:1. Also the peak-to-valley ratio of 40:1 found in the mass distribution of $^{238}U(n,f)$ for about 12 MeV excitation energy of $^{239}U$ [15] is not in contradiction to the spectrum of electromagnetic events of $^{238}U$ shown in figure 2.

Figure 3 shows the charge distributions of the fission fragments produced in the lead target from a series of fissioning isotopes. As the statistics obtained with a weak $^{238}U$ beam of $10^5$ particles per second on the average was rather low, it was not attempted to isolate the electromagnetic fission events. However, it is clearly observed that a transition from symmetric to asymmetric fission occurs with increasing mass of the fissioning system. This transition is well localized not too far away from the nucleus $^{226}Ra$ in the vicinity of which

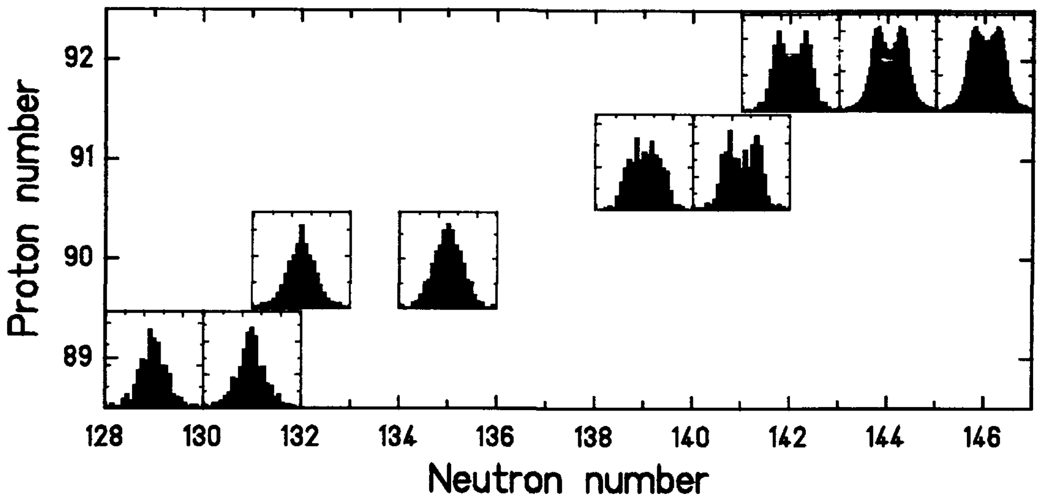


Fig. 3: Nuclear-charge distributions of the fission fragments observed behind a lead target from a series of isotopes. The distributions are centered at the positions of the fissioning nuclei on a chart of nuclides.

Konecny et al. [5] have studied the two fission modes in detail. Together with their data, the data presented here indicate that the transition from mass-asymmetric fission, observed around $^{233}U$ to $^{238}U$, to mass-symmetric fission, observed near $^{208}Pb$, occurs at a neutron number of about 138. The proton number of the fissioning nucleus seems to be less decisive for this transition.

In summary, the present article describes the first successful application of a new experimental technique to study low-energy fission of a large variety of fissionable nuclei. We hope, that forthcoming results obtained with this novel approach will stimulate this old but still exciting field of nuclear physics and that it will yield new information on the dynamic evolution of nuclear matter at low temperatures where nuclear structure plays an important role.

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