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Measurement of the average multiplicity of prompt-fission-neutrons from ^{238}U(n,f) and ^{235}U(n,f) from 0.7 to 200 MeV

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Abstract. Prompt-fission-neutron multiplicities were measured at a "white" neutron source for the fission of ^{238}U and ^{235}U up to 200 MeV. The data are of great importance in the connection of accelerator-coupled nuclear reactor systems incinerating actinides, with uranium considered as a prototype actinide. We report that the fission induced by 200 MeV neutrons produces ≈10 more prompt neutrons than the fission induced by reactor neutrons.

INTRODUCTION

Interest in obtaining a more detailed understanding of prompt neutron emission in fission is now high. Efforts are being pursued in measuring [1, 2] and modeling [3, 4, 5, 6, 7, 8, 9] prompt-fission-neutron properties from low to intermediate energies. The data are of great importance in the connection of accelerator-coupled nuclear reactor systems (or accelerator-driven systems, "ADS") burning and incinerating actinides, with uranium considered as a prototype actinide [10]. The spallation reactions used to relax the neutron economy of fast nuclear reactors reach to high energy neutrons, which are investigated in this work. Moreover, these data provide valuable information to improve our understanding of fission at high excitation energy. In particular, it is interesting to investigate in which proportions the heated system releases the excess energy with pre-fission neutron and light charged particle (LCP) emission and increase of excitation energy and angular momentum of the primary fragments. Prompt-fission-neutron multiplicities (which average is usually denoted $\bar{\nu}_p$) for neutron-induced fission of uranium were measured by Fréhaut [11] in the 1970's from 1.5 to 28 MeV for ^{235}U and ^{238}U. Howe et al. [12] completed the measurement up to 49 MeV for ^{235}U(n,f) in the 1980's. But beside points on ^{238}U(p,f) at energies below 60 MeV[14], only one measurement was reported at intermediate energies at 156 MeV [13]. The availability of an intense "white" neutron source combined with an efficient fission vs. neutron coincidence setup made it possible to investigate prompt fission neutron spectra for the first time for ^{238}U(n,f) over a wide range of energies [1]. The results reported in this letter for both ^{238}U(n,f) and ^{235}U(n,f) for $\bar{\nu}_p$ bear important information on the emission process that imply consequences on the design of industrial applications of nuclear fission at intermediate energies.

EXPERIMENTAL RESULTS

Two methods are commonly used to measure prompt neutron fission multiplicities. The first one consists in detecting the neutrons emitted in the reaction with a large, nearly 4π, Gd-loaded liquid scintillator ball. The method is appropriate for absolute measurements of the first and second moments of the multiplicity distribution with a good precision since most neutrons, low to high energy, are detected [11]. However, it is not well suited for measurements on a wide incident neutron energy range as it requires long irradiation times with mono-energetic beams. Also, no information on the energy of the detected neutrons can be obtained. The second method utilized in this work consists in detecting the neutrons with smaller liquid scintillators at a distance from an active target. The time-of-flight technique is used to determine the emitted neutron energy to build the fission neutron spectrum (FNS) and the incident neutron energy [12]. A quantity proportional to $\bar{\nu}_p$ is simply obtained from the ratio of the integration the FNS to the number of fission events. The measured quantities depend on the detection angles and energy thresholds, and therefore they have larger systematic errors than the Gd detector data. However, the technique is well suited to measurements

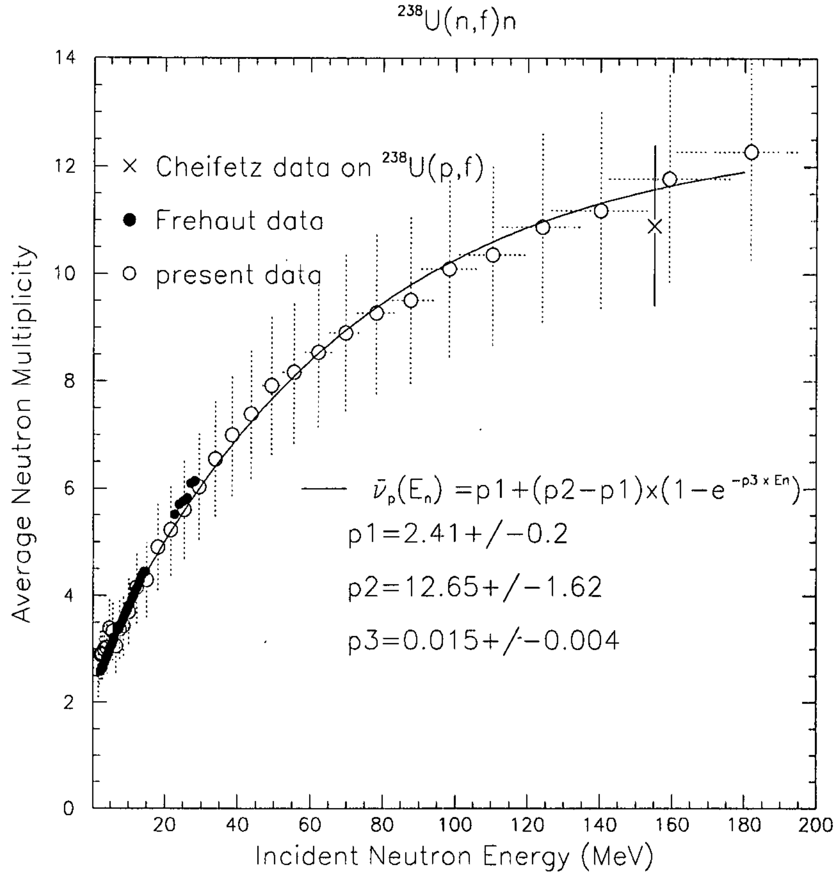

FIGURE 1. Prompt fission neutron average multiplicity for the system ^{238}U(n,f) as a function of incident neutron energy (open circles). One ^{238}U(p,f) experimental point is plotted (×) [13]. Data from [11] are plotted with black dots.

with a white neutron source, and permits the investigation of angular distributions. The measurements reported here were carried out on the FIGARO beam line [15] at the WNR spallation source of fast neutrons and the details of the analysis are discussed in [1]. The experiment with uranium 238 (235) was performed with a proton micro-pulse spacing of 1.8 μs (4.3 μs). A fission chamber containing 382 mg (348 mg) of pure uranium 238 (235) was situated at 22 m from the neutron source and used as an active target for fission events. The chamber was composed of 94 stainless steel plates each 0.1 mm thick, onto which 1 mg/cm^2 uranium was deposited onto each side. The plate separation was 0.7 mm. The chamber was filled with 99.8% Ar and 0.2% N_2 gas at a pressure of 6.5 bar. The best time resolution, 7 ns (FWHM), which was limited by the large capacitance of the detector, was obtained with a 300 V bias through an Ortec 142C preamplifier. Three neutron detectors were used for the analysis. The liquid scintillator cells were cylinders of 12.5 cm diameter and 5 cm height. The center faces were positioned at 1.143, 1.143 and 1.143 m (0.905, 0.905 and 0.875 m) from the target and at angles 105, 90 and 120 deg. (116, 71 and 85 deg.). The efficiency of the neutron detectors was determined relatively to a reference spectrum which was calculated at 1.5 MeV incident neutron energy (E_n) with the Los Alamos model (see next section). The ratio of the experimental spectrum around 1.5 MeV to the reference spectrum was fitted to a 6th order polynomial. The ratio was normalized at the maximum of the spectrum, i.e. between 1 and 2 MeV detected neutron energy. The low and high energy parts of the spectra were not exploitable, therefore the efficiency was set to 0 for neutron energies below 0.8 MeV and above 7.5 MeV. The relative average neutron multiplicities were simply computed from the integration of the FNS distributions divided by the number of fission in the incident neutron energy bins. Our data are normalized (using least square minimization) to reference data [11] between 1.5 and 28 MeV incident neutron energy. The experimental values for ^{238}U(n,f) (^{235}U(n,f)) are plotted in Fig.1 (Fig. 2). The vertical error bars represent the systematic errors from the normalization, the horizontal ones represent the in-

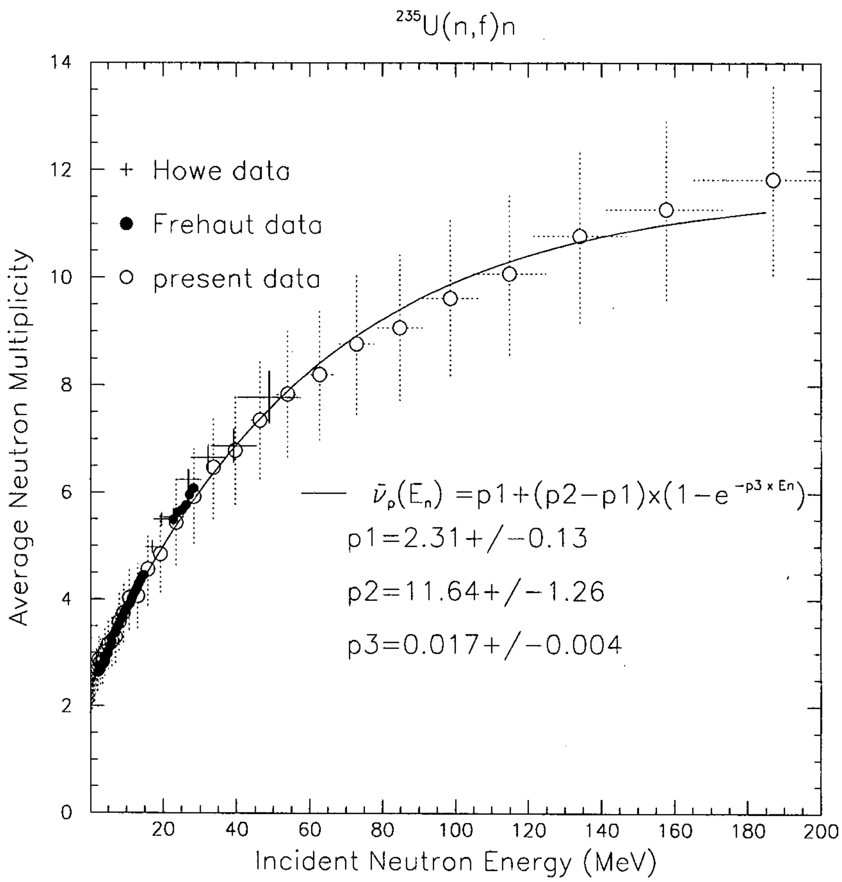

FIGURE 2. Prompt fission neutron average multiplicity for the system ^{235}U(n,f) as a function of incident neutron energy (open circles). Data from [11] are plotted with black dots and data from [12] with a +.

coming neutron energy precision.

At low energy, our data agree well with the data of Frehaut [11]. From 8 to 28 MeV incident neutron energy, the agreement is remarkable. In particular the slope at low energy of the data, i.e. $\frac{d\bar{\nu}_p}{dE_n} = (7.4MeV)^{-1}$, is found to be in agreement with reported values [16]. Existing sparse data points [12, 13] at higher energies are also presented for comparison. The neutron detectors in the case of [13] were at 90 degrees to the beam. There was also a coincidence required between the fission fragment (one detector at 90 degrees to the beam and the other in the forward direction). The plan was to detect neutrons at 90 or 0 degrees relative to the fission fragments. In other words, there were similarities and differences with our work. Similar to our work, the neutrons were not detected in the forward direction. Different from our work, a coincidence was required with fission fragments at two chosen angles. One should also note that the fissility of the p+^{238}U system is greater than that of n+^{238}U and so the two may not be directly comparable. The present $\bar{\nu}_p$ data follow a simple exponential function : $\bar{\nu}_p(E_n) = p1 + (p2 - p1)(1. - exp(-p3 \times E_n))$ where p1 represents the value of $\bar{\nu}_p$ at very low energy, and p2 the extrapolation of the maximum number of emitted neutrons at very high energies. This function was used by Wahl to parameterize fission yield systematics up to 200 MeV [17]. The data were fitted with this simple function. The fit parameter values are given in the plots. One can see that the difference between neutrons emitted in the fission of uranium 238 and 235 increases from 4% at low energies to 9% at 200 MeV. At this energy, one more neutron is emitted on average for uranium 238.

CONCLUSION

In conclusion, new data on $\bar{\nu}_p$ are reported with errors $\leq$ 15%. $\bar{\nu}_p$ grows steadily in the fission of ^{238,235}U induced by neutrons up to 200 MeV. At this energy, it exceeds by $\approx$ 10 the number of neutrons from fission induced by reactor neutrons. Uranium 238 shows enhanced neutron emission compared to uranium 235 due to the higher mass and lower binding energy of the neutrons. In future experiments, we plan to investigate on a much broader range the energy and the angular distributions of the emitted neutrons to improve the precision of the data.

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