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Investigating Prompt Fission Neutron Emission from ^{235}U(n,f) in the Resolved Resonance Region

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Abstract. Investigations of prompt emission in fission is of importance in understanding the fission process in general and the sharing of excitation energy among the fission fragments in particular. Experimental activities at IRMM on prompt neutron emission from fission in response to OECD/NEA nuclear data requests is presented in this contribution. Main focus lies on currently on-going investigations of prompt neutron emission from the reaction ^{235}U(n,f) in the region of the resolved resonances. For this reaction strong fluctuations of fission fragment mass distributions and mean total kinetic energy have been observed [Nucl. Phys. A 491, 56 (1989)] as a function of incident neutron energy in the resonance region. In addition fluctuations of prompt neutron multiplicities were also observed [Phys. Rev. C 13, 195 (1976)]. The goal of the present study is to verify the current knowledge of prompt neutron multiplicity fluctuations and to study correlations with fission fragment properties.

1 Introduction

Prompt neutron emission in fission is of particular importance in understanding the fission process. Knowledge of the properties of prompt fission neutrons, their multiplicities and energy distributions could give answers to questions related not only to the neutron emission itself, but also to questions relevant to the formation of the fission fragments, the sharing of excitation energy among them and the time scale of the process. For nuclear modeling and improved evaluation of nuclear data the knowledge about fluctuations in the prompt neutron multiplicity as a function of incident neutron energy is requested for the major actinides ^{235}U and ^{239}Pu [1, 2]. Fluctuations in fission fragment mass and total kinetic energy (TKE) in both isotopes have been observed in resonance neutron induced fission [3, 4]. Independently, fluctuations in the number of emitted neutrons have also been observed [5]. In view of the fact that both neutron number and fission fragment properties have been found to vary it is necessary to study the correlations of prompt neutron multiplicity and fission fragments properties in the resonance region. Experimental investigations of the correlations of prompt fission neutron multiplicity with fragment properties in resonance neutron induced fission on ^{235}U and ^{239}Pu, are taking place at the GELINA facility of the JRC-IRMM.

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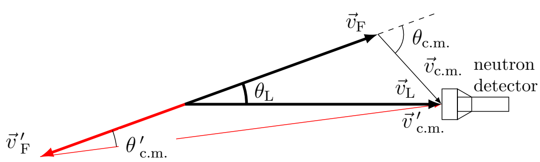
2 Experimental Method

The experimental technique used to study prompt neutron emission in fission at the GELINA facility is based on techniques pioneered by Bowman [6]. The method involves extracting fission fragment masses by measurement of either velocity (2v) or energy (2E) of the two fragments, and coincident measurement of fission neutron time-of-flight at known angles with respect to the fission axis. This gives the basic information needed for reconstructing the neutron emission in the rest frame of the fully accelerated fragment, cf. Fig. 1. In an experiment on prompt fission neutrons from ^{252}Cf(sf), Budtz-Jørgensen et al. [7] exploited the combination of a twin Frisch-grid ionization chamber for fission fragment properties (2E technique) and a liquid scintillator for neutron detection. This serves as the basis for our experimental setup (which is described in Sect. 3) to study prompt neutron emission. The ionization chamber has a large solid angle, which not only facilitates the fragment-neutron coincidence rate, but also introduces a less biased selection of coincident events.



$$v_{c.m.}^2 = v_L^2 + v_F^2 - 2v_L v_F \cos\theta_L$$
$$\cos\theta_{c.m.} = (v_L \cos\theta_L - v_F)/v_{c.m.}$$

Figure 1. Vector diagram of the kinematics of neutron emission from a fully accelerated fragment and the transformation into the fragment rest frame (c.m.), black lines represent the fragment detected in the same hemisphere as the neutron, while red lines represent the complimentary fragment. Vectors and angles drawn with thick lines are directly measured in the experiment. The labels are; fragment velocity $\vec{v}_F$, complimentary fragment velocity $\vec{v}\,'_F$, neutron velocity in the laboratory frame $\vec{v}_L$ and neutron velocity in the center-of-mass frame $\vec{v}_{c.m.}$.

2.1 Prompt Fission Neutrons from ^{252}Cf(SF)

An experimental investigation of prompt fission neutron multiplicity correlations with fission fragment properties in the spontaneous fission of ^{252}Cf was undertaken to verify setup and analysis procedures relevant for studying neutron emission in resonance-neutron induced fission. Beside the purely experimental interest, recent advances in the theoretical description of prompt emission in fission [8–10] require detailed correlation data for verifying the models. The experiment is essentially a reproduction of the experiment performed by Budtz-Jørgensen et al. [7] with the traditional analog acquisition system now replaced by a fully digital one and subsequent digital signal processing. Experimental details and main results have been published elsewhere [11], for the sake of clarity, a few selected results will be presented in the following. On the left hand side of Fig. 2 the mean number of neutrons emitted per fission is shown as a function of the TKE of the fission fragments, the dependence is nearly linear (except for at low TKE). A least square fit to the data from the present experiment gives an inverse slope of (12.6 ± 0.2) MeV/n. Due to the correlation between TKE and fragment mass distributions this quantity must not be interpreted as the energy needed for a pair of fragments to emit one more neutron, as noted already in Ref. [18]. The discrepant data from Refs. [12, 13] can be explained by failure in taking into account the recoil energy imparted to the fission fragment by the detected neutron [19]. A detailed discussion of this can be found in Ref. [11]. The mass dependence of the prompt fission neutron multiplicity per fragment from this experiment is compared to literature data [7, 14–17] in the right hand side of Fig. 2. The data from this study agree quite well with experimental data available in the literature.

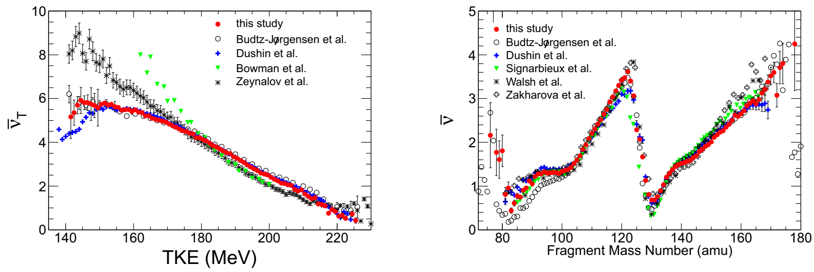


Figure 2. Left: Average neutron multiplicity per fission as a function of TKE, in comparison with experimental data from literature [7, 12–14]. Right: Average prompt fission neutron multiplicity as a function of fission fragment mass, in comparison with data from literature [7, 14–17].

3 Setup for the ^{235}U(n,f) Experiment

The experimental setup for investigating correlations of prompt neutrons with fission fragments in resonance-neutron induced fission on ^{235}U and ^{239}Pu is illustrated in Fig. 3. The fission target is placed inside the ionization chamber about 9.2 m away from the neutron production target of the GELINA facility. An array of neutron detectors (SCINTIA) is employed in order to facilitate the fission-neutron coincidence count rate. The SCINTIA array consists of 7 NE213 equivalent liquid scintillators (Scionix LS-301) and 5 para-therphenyl detectors. When employing an array of neutron detectors, each detector forms an axis of symmetry around which the orientation of the fission axis needs to be known. Hence the traditional ionization chamber is no longer sufficient to reconstruct the kinematics in the fragment rest frame. To remedy the situation, the ionization chambers anode plate is replaced by a position sensitive readout structure, which allows determination of all three space components of the fission fragments direction of travel. A 22 channel fully digital data acquisition is used. For each fission event the digital waveforms of all channels, sampled at 400 MS/s with 14-bit resolution, are stored on disk for off-line treatment. A register counting the number of oscillations of the sampling clock (800 MHz) is reset by a pulse generated just before the electron bunch from the GELINA hits the neutron production target. The value of the register as the fission trigger arrives is stored together with the waveform data, giving the incident neutron time-of-flight for each event. In Fig. 4 a time-of-flight spectrum of the ongoing ^{235}U(n,f) experiment is displayed.

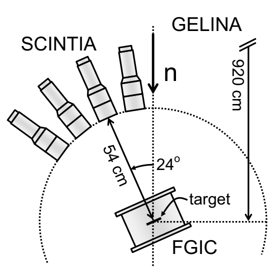


Figure 3. Schematic view of the experimental setup for investigating resonance neutron induced fission.

4 Preliminary results on ^{235}U(n,f)

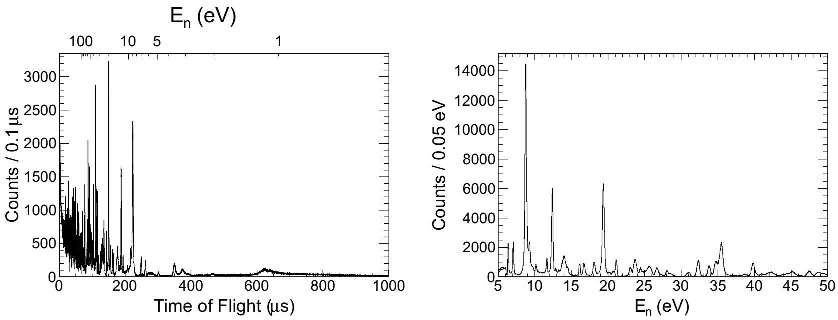


Figure 4. Left: Incident neutron time of flight spectrum from the ongoing experiment on ^{235}U(n,f). Right: The same spectrum converted to incident neutron energy in the range [5,50] eV (right).

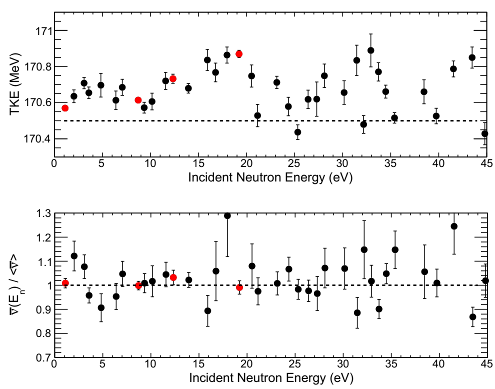


Figure 5. Top: Average TKE as a function of incident neutron energy for given resonance or resonance group in the range up to 45 eV, the dashed line refers to the thermal value. Bottom: Neutron multiplicity for the same resonances or resonance groups relative to the weighted average neutron multiplicity. The red points highlight strong resonances in the fission cross section of ^{235}U.

The top panel of Fig.5 shows the average TKE as a function of incident neutron energy in the range up to 45 eV. Each point corresponds to either a single resonance or resonance group. The red points highlight the strongest resonances in the fission cross section of ^{235}U. A clear fluctuating behavior exceeding the experimental uncertainty is observed. This was already pointed out in Ref. [3]. However, the statistical significance is much improved in the present work leading to a clearer picture of the energy dependent changes compared to the earlier work. The lower panel of Fig. 6 shows the neutron multiplicity for a given resonance or resonance group relative to the weighted average neutron multiplicity. Again, the strongest resonances are highlighted in red. At the current moment of data collection, an anti-correlation, i.e., high TKE corresponding to lower neutron multiplicity, is observed when all points in the given incident neutron energy interval are plotted. This is expected from energy conservation. Of course, also possible changes in the mass distribution need to be accounted for. Nevertheless, there seem to be no sizeable fluctuations in the neutron multiplicity in the strong resonances.

5 Conclusions

An investigation of prompt fission neutrons and fission fragments in the spontaneous fission of ^{252}Cf has been performed as a preparatory step to investigate prompt fission neutron emission in resonance-neutron induced fission. A literature comparison of the results show that the experimental setup and analysis is under control.

Prompt fission neutron and fission fragment correlations in resonance neutron induced fission on ^{235}U are taking place at the GELINA facility of the IRMM. We are confident that the new data will shed light in the understanding of the observed neutron multiplicity fluctuations in the resonance region and the behavior of the neutron multiplicity as a function of mass and incident neutron energy.

Acknowledgements

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