Neutron-Induced Fission Cross Sections of Nuclei in the Vicinity of $^{208}$Pb at Incident Energies below 60 MeV


*V.G. Khlopin Radium Institute, 194021 Saint-Petersburg, Russia
†FNRS and Institute of Nuclear Physics, Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium
§Physikalisch-Technische Bundesanstalt, D-38116 Braunschweig, Germany

Abstract. Neutron-induced fission cross sections of $^{205}$Tl, $^{204}$, $^{206}$, $^{207}$, $^{208}$Pb, and $^{209}$Bi have been measured at incident energies of 32.8, 45.3, and 59.9 MeV. The measurements were performed at the Louvain-la-Neuve neutron beam facility using the $^7$Li ($p$, $n$) reaction as neutron source. Fission fragments were detected with a multi-section Frisch-gridded ionization chamber (MFGIC). Neutron fluence measurements were based on the $^{238}$U($n$, f) reaction. The neutron fluence monitoring procedure was asserted by crosscheck measurement, in which the 59.9-MeV neutron beam fluence was simultaneously determined with the MFGIC and with a fission chamber monitor calibrated relative to a proton-recoil telescope.

INTRODUCTION

Neutron-induced fission of nuclei in the vicinity of lead is the subject of both applied and basic studies. In terms of applications, lead- and bismuth-related data are of interest for the feasibility studies of the accelerator driven systems (ADS). In fact, the lead-bismuth eutectic is presently considered as the most appropriate material for the neutron production target. The proper conceptual analysis of ADS requires target performance parameters such as the number of outgoing neutrons, their spectrum, the prompt and residual radioactivity, the heat release, the radiation resistance (in the case of solid target), etc. To one extent or another, all these parameters depend on the neutron-induced fission reactions occurring in the target material.

Similarly, the low-energy data are of particular interest for the nuclear fission studies because of a possible manifestation of quantum effects related to almost or completely filled (as for $^{208}$Pb) neutron and proton shells as excitation energy decreases. A better understanding of this phenomenon will contribute to the development of the dedicated nuclear reaction models and computer codes, which might be used for creation of the evaluated nuclear data libraries at intermediate energies.

In this work [1], we have measured the neutron-induced fission cross sections of $^{205}$Tl, $^{204}$, $^{206}$, $^{207}$, $^{208}$Pb, and $^{209}$Bi in the neutron energy range from 35 to 175 MeV. The present work was undertaken in order to refine these data as well as to extend the incident energy range towards the low-energy domain.

EXPERIMENTAL SET-UP

The measurements were performed at the Louvain-la-Neuve (LLN) neutron beam facility. The quasi-monoenergetic neutrons with peak energies of 32.8, 45.3, and 59.9 MeV were produced by the $^7$Li($p$, n)$^7$Be reaction using a 5-mm-thick natural lithium target and a steady proton beam current of about 10 μA throughout 168 hours.

Fission fragments were detected with a multi-section Frisch-gridded ionization chamber (MFGIC). The MFGIC is a stack of seven twin ionization chambers with Frisch grids. The electrode assembly
of the MFGIC is shown in Fig. 1. It is housed in a thin-walled cylindrical detector shell of 200 mm diameter and 520 mm length. The anodes and cathodes are 50-µm-thick duralumin foils sandwiched between two rings with inner and outer diameters of 140 and 170 mm, respectively. The gas mixture is composed of 90% argon and 10% methane (P-10). The chamber operates at atmospheric pressure without a continuous gas flow.

The detector was loaded with sub-actinide targets under study plus a natural uranium target (deposited in the form of natUF₄) as a reference target. The fissile materials were deposited (by thermal vacuum evaporation) on each side of cathode foils stretched between the supporting rings. The diameter of each target was 80 mm. The total fissile mass of the reference target was measured by alpha-counting, while the masses of the sub-actinide targets (pure metals) were determined by weighting. The total masses of fissile deposits for the backward / forward target faces are indicated in Fig. 1. For all targets, the uncertainty in the mass was not larger than 2%.

![FIGURE 1. Electrode assembly of the multi-section Frisch-gridded ionization chamber.](image)

The detector was so positioned that the reference target was at a distance of 10.2 m from the neutron production target. At this position the beam diameter (FWHM) was about 10 cm with an average fluence rate of peak neutrons of about 2·10⁴ / (cm²·s).

DATA ANALYSIS AND CORRECTIONS

Using the method detailed in [2], the distributions of fission events over the neutron time-of-flight (TOF) have been obtained for each target as well as the fission fragment energy and angular distributions.

Neutron fluence measurements were based on the ²³⁵U(n, f) standard [3]. In order to derive the fluence of peak neutrons, a decomposition of the reference TOF spectra has been done as described in [4]. The same procedure has been applied to the TOF spectra obtained for the sub-actinide targets in order to extract the number of fission events induced by peak neutrons.

The neutron fluence monitoring procedure has been asserted by crosscheck measurement in which the fluence of 59.9-MeV neutrons has been simultaneously determined with the MFGIC and a fission chamber monitor (FCM) calibrated relative to a proton recoil telescope [5]. The fluence of peak neutrons determined with the FCM (placed at a distance of 6 m from the Li-target) was related to the MFGIC position using the 1/ᵣ² law and by taking into account the neutron absorption in the air. The results of the inter-comparison were found to be consistent within 3%.

The fission cross sections were calculated as follows:

\[
\sigma_f = \frac{k_u k_L}{2 \Phi_0} \left( \frac{N_f^B}{\epsilon_F N_A^B} + \frac{N_f^P}{\epsilon_P N_A^P} \right),
\]

where \( \Phi_0 \) denotes the fluence of peak neutrons at the reference target position, \( k_u \) is the correction for the isotope composition of the target, \( k_L \) is the fluence correction for the target position along the neutron beam axis, \( \epsilon_F(B) \) is the detection efficiency, \( N_A^{F(B)} \) is the number of fissile nuclei, and \( N_f^{F(B)} \) is the number of fission events due to peak neutrons. The superscripts \( F \) and \( B \) in the above expression denote the forward- and backward-facing targets, respectively.

The efficiency of fission fragment detection \( \epsilon \) was obtained as the product of two correction factors allowing for fission fragment absorption in the target and the loss of events due to pulse-height threshold. A detailed discussion of these corrections is given in [1].
RESULTS

The neutron-induced fission cross sections of $^{205}$Tl, $^{204,206-208}$Pb, and $^{209}$Bi obtained in the present work are listed in Table 1 and shown in Fig. 2. The first column of Table 1 displays the mean energies of neutron peaks and their FWHM. The $^{204}$Pb data are also presented in Table 1. They were derived from the cross sections of the separate lead isotopes. The cross-section uncertainties are one standard deviation. A comparison of the present data with those obtained in [1] is also shown in Fig. 2. All these results are consistent within their uncertainties. The higher accuracy of the present data results from the excellent characteristics of the LLN neutron beam.

FIGURE 2. Measured neutron-induced fission cross sections of $^{205}$Tl, $^{204,206-208}$Pb, and $^{209}$Bi as a function of incident neutron energy. The solid circles represent the results of the present work and the open circles correspond to the data from [1].
ACKNOWLEDGMENTS

We wish to thank the operating team of the LLN cyclotron, and in particular Dr. G. Ryckewaert, for the excellent neutron beams delivered for these experiments.

This work was partially supported by the International Science and Technology Centre (project #1309).

REFERENCES

1. Tutin G.A. et al., contribution to this conference.