Cumulative fission product yields measurements with 2.8 MeV quasi-monoenergetic neutron induced fission of 232Th

Authors: Bo Gao, Lan, Prof. Chang-lin, XIE, Dr. Bo, Jiang, Mr. Gong, Wang, Mr. Jiahao, Yanliang Chang, Xu, Mr. Kuozhi, Pan, Mr. Jianglong, Wei, Dr. Yuting, Pan, Dr. Xiaodong, Nie, Mr. Yangbo, Prof. Shilong Liu, Dr. Xichao Ruan, Yang, Dr. Yi, Dr. KL Shi, Lan, Prof. Chang-lin

Date: 2025-10-21T11:47:33+00:00

Abstract

The fission yield data about neutron induced fission of 232Th play a crucial part in generation-IV thorium- based molten salt breeder reactor designs and evaluation the impact of decay heat in nuclear fuel cycle scenarios. The 232Th(n,f) reaction cumulative fission product yields were measured at the average neutron energy of 2.8 MeV using the activation method and off-line γ-ray spectrometric technique. The 2.8 MeV quasi-monoenergetic neutron beam was provided the CPNG-600 Cockcroft Walton accelerator based on D(d,n)3He reaction at the China Institute of Atomic Energy (CIAE). The neutron fluence fluctuation was determined using the associated 3He particle method. The induced γ-ray activities of cumulative fission products were measured by a low background with a high purity germanium (HPGe) γ-ray spectrometer. Following sufficient consideration and corrections the sources of uncertainty, high precision cumulative yields of nine fission products were obtained. Our cumulative FPYs for the 232Th(n,f) reaction at 2.8 MeV were compared with the existing experimental nuclear reaction data and evaluated data of ENDF/B-VIII.1, JEFF-3.3 and JENDL-5 in a wide range of neutron energies. Meanwhile, cumulative FPYs of 232Th(n,f) reaction was also calculated using the TALYS-1.96 code to contrast and analyze the result with the present data. The experiments have produced valuable results on FPYs for 232Th in neutron fields of 2.8 MeV neutron energy. The results also enable an update of the cumulative FPYs by incorporating the latest nuclear data (emission intensities and half-lives), along with a detailed discussion of the associated uncertainties. The fission yield data will be provided valuable insights for the design of Gen-IV reactors and the establishment of evaluated fission yield databases.

Full Text

Preamble

Cumulative fission product yields measurements with 2.8 MeV quasi-monoenergetic neutron induced fission of ^{232}Th

Bo Gao[1], Chang-lin Lan[1],†, Bo Xie[1], Gong Jiang[1], Jia-hao Wang[1], Yan-liang Chang[1], Kuo-zhi Xu[1], Jiang-long Pan[1], Yu-ting Wei[2], Xiao-dong Pan[1], Yang-bo Nie[3], Shi-long Liu[3], Xi-chao Ruan[3], Yi Yang[3], and Ke-liang Shi[1]

[1]School of Nuclear Science and Technology, Lanzhou University, Lanzhou 730000, China
[2]Institute of Modern Physics, Chinese Academy of Science, Lanzhou 730000, China
[3]Key Laboratory of Nuclear Data, China Institute of Atomic Energy, Beijing 102413, China

Fission yield data for neutron-induced fission of ^{232}Th play a crucial role in Generation-IV thorium-based molten salt breeder reactor designs and in evaluating the impact of decay heat in nuclear fuel cycle scenarios. The cumulative fission product yields (FPYs) for the ^{232}Th(n,f) reaction were measured at an average neutron energy of 2.8 MeV using the activation method combined with off-line γ-ray spectrometry. The 2.8 MeV quasi-monoenergetic neutron beam was provided by the CPNG-600 Cockcroft-Walton accelerator based on the D(d,n)^{3}He reaction at the China Institute of Atomic Energy (CIAE). Neutron fluence fluctuation was determined using the associated ^{3}He particle method. The induced γ-ray activities of cumulative fission products were measured with a low-background high-purity germanium (HPGe) γ-ray spectrometer. Following thorough consideration and correction of uncertainty sources, high-precision cumulative yields were obtained for nine fission products.

Our cumulative FPYs for the ^{232}Th(n,f) reaction at 2.8 MeV were compared with existing experimental nuclear reaction data and evaluated data from ENDF/B-VIII.1, JEFF-3.3, and JENDL-5 across a wide range of neutron energies. Additionally, cumulative FPYs for the ^{232}Th(n,f) reaction were calculated using the TALYS-1.96 code to contrast and analyze the results with our experimental data. These experiments have produced valuable results on FPYs for ^{232}Th in 2.8 MeV neutron fields. The results also enable an update of the cumulative FPYs by incorporating the latest nuclear data (emission intensities and half-lives), along with a detailed discussion of the associated uncertainties. This fission yield data will provide valuable insights for the design of Gen-IV reactors and the establishment of evaluated fission yield databases.

Keywords: ^{232}Th(n,f) reaction, D-D neutron source, Activation method, Cumulative fission yield

Introduction

Energy sources constitute a critical material foundation for national economic development. The current global energy structure remains dominated by fossil fuels such as coal, oil, and natural gas. Heavy reliance on fossil fuels leads to greenhouse gas emissions, particularly carbon dioxide (CO_2), which is the primary driver of climate change. Furthermore, the finite and non-renewable nature of fossil fuel resources poses significant risks to energy security. As a low-carbon, energy-dense power source, nuclear energy represents a critical pathway for sustainable development, making its expansion consistent with worldwide energy transition strategies. The Thorium Molten Salt Reactor (TMSR), recognized as one of the six internationally acknowledged Gen-IV nuclear reactor technologies, has attracted significant attention due to its abundant fuel reserves, inherent passive safety features, waste minimization potential, and unparalleled modularity.

On April 21, 2025, the Chinese Academy of Sciences (CAS) announced a significant breakthrough in nuclear energy technology: the TMSR project has transitioned to thorium-based operation, marking the first deployment of a liquid-fueled Gen-IV reactor in Wuwei, Gansu Province. TMSR operation is based on the efficient utilization of the thorium-uranium fuel cycle (^{232}Th-^{233}U). In contrast to the conventional uranium-plutonium fuel cycle (based on ^{235}U/^{238}U-^{239}Pu), TMSR employs thorium-232 (^{232}Th) as a fertile material, which is transmuted into the fissile isotope uranium-233 (^{233}U) through the nuclear reaction process $^{232}\mathrm{Th} + \mathrm{n} \rightarrow {}^{233}\mathrm{U}$, thereby enabling a sustainable fuel cycle mechanism for nuclear power generation. As a key transmutation nuclide in the ^{232}Th-^{233}U fuel cycle, relevant nuclear data for ^{232}Th provide essential support for TMSR development and technological applications. Fission product yields, as a crucial component of nuclear data, represent one of the key research priorities in neutron nuclear data studies. Accurate reference data on ^{232}Th FPYs are vital for fission energy calculations, burnup analysis, neutron flux estimation, and safety assessments in TMSR. Notably, fission product yields serve as key indicators for quantifying fission events in neutron-irradiated samples [**?**].

In contrast to the ^{235}U/^{238}U-^{239}Pu fuel cycle, existing yield nuclear data for the ^{232}Th-^{233}U fuel cycle are limited overall. The EXFOR nuclear reaction database documents over 30 experimental datasets reporting cumulative FPYs across neutron energies spanning 0.025 eV to 14.8 MeV. However, available measurements are predominantly concentrated in the D-T energy range, while data for D-D energies remain notably insufficient [**?**].

In the D-D neutron source energy range, as illustrated in Fig. 1 [Figure 1: see original paper], K.M. Broom (1964) [**?**] conducted experimental determinations of cumulative FPYs induced by 2.95 MeV neutrons for products spanning ^{91}Sr to ^{139}Ba, while D.L. Swindle et al. (1971) [**?**] subsequently measured fission products ranging from ^{77}As to ^{156}Sm. In reactor environments, A. Turkevich et al. (1951) [**?**] measured cumulative FPYs for isotopes ranging from ^{72}Zn to

^{144}Ce at an average incident neutron spectrum energy of 2.70 MeV. Similarly, H.N. Erten et al. (1981) [**?**] determined cumulative FPYs for products between ^{77}Ge and ^{153}Sm at 3.30 MeV, while A.E. Richardson et al. (1986) [**?**] reported cumulative yields for ^{83}gSe and ^{130}gSb at 3.35 MeV.

Fig. 1. Cumulative FPYs data of ^{232}Th in the existing literature.

In the aforementioned literature, cumulative fission yield data were obtained solely through laboratory measurements for a limited number of nuclides, with the majority published prior to the 1990s. To address data scarcity for cumulative FPYs in the D-D energy range, we conducted an investigation of fission induced by 2.8 MeV neutrons on ^{232}Th. The objective of this work is to perform a thorough, high-precision, self-consistent study that provides accurate relative FPY information in the D-D energy range of fission-spectrum neutrons.

The experiments have produced valuable results on FPYs for ^{232}Th in 2.8 MeV neutron fields. These results also enable an update of the cumulative FPYs by incorporating the latest nuclear data (emission intensities and half-lives), along with a detailed discussion of the associated uncertainties.

II. Experimental Details

A. Experiment Method

Neutron activation analysis is a modern nuclear analytical technique widely employed in nuclear data measurements. In this work, the activation method combined with off-line γ-ray spectrometry was utilized to measure ^{232}Th(n,f) reaction cumulative fission product yields at an average neutron energy of 2.8 MeV. This approach is characterized by high sensitivity, exceptional accuracy, non-destructiveness, and the capability for simultaneous multi-nuclide analysis through characteristic off-line γ-ray spectroscopy.

The process begins with preparation of a neutron source and sample target. Neutrons are irradiated onto the sample target, causing stable nuclides in the sample to absorb neutrons and undergo nuclear reactions, thereby producing radioactive nuclides. These radioactive nuclides subsequently decay, emitting characteristic γ-rays—a process known as neutron activation. After irradiation, the sample is allowed to cool for a period of time. The activity of the irradiated sample is then measured using γ-spectrometry instruments such as HPGe or NaI(Tl) detectors to obtain radioactive information. Finally, based on the characteristic peaks in the γ-spectrum, the nuclides present in the sample are identified and quantified. The cumulative FPY of the nuclides is calculated using the areas of the characteristic γ-ray peaks. It should be noted that corrections to nuclide yields and analysis of various uncertainty sources are also essential.

B. Neutron Source

The 2.8 MeV quasi-monoenergetic neutron beam was produced by the CPNG-600 Cockcroft-Walton accelerator neutron source based on the D(d,n)^{3}He reaction at the China Institute of Atomic Energy (CIAE) by bombarding a Ti-D target with a 300 keV deuteron beam [**?**]. Neutron fluence fluctuation was determined using the associated ^{3}He particles from the D-D reaction detected by an Au-Si surface barrier detector. Based on this method, the mean neutron flux was measured to be 1.4×10^9 (/s). The average neutron energy was calculated using the Q-equation of the nuclear reaction. Table 1 depicts the parameters of the neutron source used in this experiment.

C. Target Preparation and Irradiation

The ^{232}Th sample is a pellet fabricated by pressing ThO_2 powder with a purity of 99.99%, having a mass of 1.7715 g and a diameter of 20 mm. Zn, In, and Al foils (all with purity higher than 99.9% and diameter of 20 mm) were selected as neutron fluence monitors to determine the neutron fluence received by the sample. The samples were packaged in the order of Th-Zn-In-Al and prepared for irradiation, as shown in Fig. 2 [Figure 2: see original paper].

The irradiation experiment was performed at the CPNG-600 Cockcroft-Walton accelerator facility of CIAE, with the target foil mounted in direct contact with the beam tube end-plate. The experimental setup is shown in Fig. 2. The ^{232}Th sample pellet was positioned at 0° relative to the beam direction, 3.8 cm from the target. A 300 keV deuteron beam was accelerated to produce a 2.8 MeV quasi-monoenergetic neutron beam via the D(d,n)^{3}He reaction for irradiating the ThO_2 samples.

Considering the relatively small neutron-induced fission cross-section of ^{232}Th (approximately 1.29$×10^{-27}$ m^2 at 2.8 MeV), an extended irradiation period of 19.05 hours was employed. Throughout the irradiation process, neutron flux variation was monitored in real-time using an Au-Si surface-barrier detector to measure the accompanying ^{3}He particles from the D(d,n)^{3}He reaction, thereby tracking neutron flux non-uniformity.

TABLE 1 . The parameters of the neutron source used in this experiment.

Neutron Energy (MeV)	Nuclear Reaction	Target-to-neutron-source distance (cm)	Neutron Flux Rate (/cm^2*s)	Incident Deuterium Beam Energy (keV)
2.8$±0.3	$D(d,n)^3$He		10^6	

D. Measurement of γ-ray Radioactivity

Understanding HPGe γ-ray spectrometer detector performance is an essential prerequisite before conducting FPY measurements. The experiment was conducted using an HPGe γ-ray spectrometer with a relative efficiency of 50% (model GEM50P4) manufactured by ORTEC, USA, which achieved an energy resolution of 1.9 keV for ^{60}Co at 1.33 MeV. The γ-spectrum acquisition was performed using MAESTRO-32 software developed by ORTEC, specifically designed for HPGe detector systems. For HPGe γ-ray spectrometer detectors, energy calibration is a crucial component of the experiment. Inaccurate calibration will affect subsequent calculations of FPYs. Under identical experimental conditions, the energy calibration for a given HPGe detector remains consistent. The standard point source ^{152}Eu of known activity was selected for calibration. The γ-spectrum measurements were conducted in the low-background laboratory at CIAE. Fig. 3 [Figure 3: see original paper] presents the calibrated γ-ray spectrum, whose characteristic energies cover the entire energy range of interest. The relationship between the detected γ-ray energy and the corresponding channel address is illustrated in Fig. 4 [Figure 4: see original paper]. The full-energy peak efficiency as a function of energy was fitted with an exponential function to derive the detector efficiencies at the characteristic γ-ray energies of ^{152}Eu. The fitting parameter values are given in Fig. 5 [Figure 5: see original paper].

Fig. 2. Schematic diagram of experimental geometry.

Fig. 3. The typical ^{152}Eu γ-spectrum measured by HPGe γ-ray spectrometer.

Fig. 4. The fitted energy curve and measured energy data.

Fig. 5. The fitted efficiency curve and measured efficiency data.

The irradiation, cooling, and measurement times are adjusted according to the half-lives of the target nuclides in order to perform targeted measurements. In this experiment, following an irradiation period of 19.05 hours, the ^{232}Th sample was cooled for 0.4 h and 6.53 h, as shown in Fig. 6 Figure 6: see original paper and (b), respectively. An appropriate cooling period not only reduces the system dead time of the γ-spectrometer—facilitating acquisition of γ-spectra—but also minimizes the radiation dose received by experimenters. The ^{232}Th sample was then mounted on a pre-calibrated HPGe detector, and the full-energy peak counts of characteristic γ-rays emitted by various fission products were recorded. Finally, the aforementioned MAESTRO-32 software was used for data acquisition.

Decay curves were used to uniquely identify and determine each fission product while ensuring the absence of interfering transitions. The experimental half-lives were compared with literature values, and only those fission products showing good agreement were retained for final analysis. However, due to limitations in energy resolution, two adjacent full-energy peaks could not be sufficiently resolved. As shown in Fig. 6, hundreds of different energy characteristic γ-rays were measured by the HPGe detector. To identify whether each γ-ray is emitted

by the radionuclide of interest, the decay curve analysis method was adopted to identify the radionuclide by measuring its half-life, as discussed in our previous articles [**?**]. We take the 641.285 keV γ-ray produced by the ^{142}La nucleus as an example, which may be affected by the very close energy γ-ray (641.4 keV) from ^{147}Pr ($T_1/_2$=13.44 min, Iγ=13.44%). Because the half-life of ^{147}Pr is short, there is good consistency between the half-life obtained by periodic measurement as shown in Fig. 7 [Figure 7: see original paper] (3.33 h) and the recommended half-life (91.1 min) of ^{142}La. When the relative deviation between the experimental value and recommended value is less than 5%, the data are selected for the final fission yield calculation [**?**]. By means of this method, the characteristic γ-rays of nine fission products were identified, as shown in Fig. 6. The cumulative yield for these determined fission products will be quantitatively evaluated through the formulation presented in Eq. (1) in the following section. The decay characteristics of the product radioisotopes are summarized in Table 2.

Fig. 6. The γ-spectrum of different fission products of the ^{232}Th sample. (a) ^{232}Th sample at 3.8 cm with 2400 s lifetime; (b) ^{232}Th sample at 3.8 cm with 36000 s lifetime.

Fig. 7. Relationship between measurement time of ^{142}La and logarithm of characteristic peak counts.

TABLE 2 . Characteristics of identified fission products γ-ray.

Fission products	Half-life of product	γ-ray energy Eγ (keV)	γ-ray intensity Iγ (%)
^{132}Te	9.65$±$0.06 h		
^{139}Ba	2.611$±$0.017 h		
^{142}La	16.749$±$0.008 h		
^{143}Ce	3.204$±0.013d|||||20.83±0.08h|||||6.58±0.03h|||||82.93±0.09min|||||91.1±0.5min|||||33.039±$0 h		

III. Data Analysis

A. FPY Calculation

The derivation of the cumulative FPY calculation formula is closely related to the development of nuclear physics, the theory of radioactive decay, and the statistical nature of fission processes. The establishment of this formula underwent gradual evolution from experimental measurements to theoretical models, with continuous refinement through experimental validation and database development. Initially, research on FPYs primarily focused on experimental measurements, employing chemical separation and radioactive detection techniques to determine the relative and absolute yields of various fission products. The number of detected γ-rays under the photopeak of a specific fission product is

connected to their cumulative FPY. The cumulative FPY can be calculated by Eq. (1):

$$C = \frac{\lambda F_{\text{total}}}{\Phi \sigma_f N I_\gamma \varepsilon_\gamma e^{-\lambda t_1}(1 - e^{-\lambda t_2})} \sum_{x=1}^{n} e^{-\lambda(T_{nf} - T_{xf})} \left[1 - e^{-\lambda(T_{xf} - T_{xi})}\right]$$

where C is the net area count of the photoelectric peak of the measured characteristic γ-ray; λ is the decay constant of the fission product; F_{total} is the total correction factor; Φ is the neutron flux density; σ_f corresponds to the ^{232}Th fission cross section at the neutron energy employed in this work; N is the number of ^{232}Th atoms in the target; I_γ is the absolute intensity of the characteristic γ-ray; ε_γ is the γ-ray detection efficiency of the HPGe detector system; t_1 denotes the cooling time; t_2 denotes the instrument measurement time; T_{xi} and T_{xf} denote the start time and end time of the x-th irradiation in n times of irradiations.

Ultimately, nine characteristic γ-rays (as shown in Fig. 6) were identified to calculate the FPY. A list of the fission product radioisotopes, their half-lives, characteristic γ-ray energies, and associated intensities was summarized and given in Table 2. The corresponding nuclear data were utilized in determining the FPY values.

B. Correction Factor Calculation

In nuclear reaction data measurement by the activation method, several corrections must be applied, including isotopic impurities, neutron beam flux fluctuation, self-absorption effect, cascade summing correction, pile-up effect, scattered neutron correction, dead time correction, and so forth. The main correction factors and primary uncertainty sources are introduced in this section.

1. Isotope correction

Isotopic correction of the sample is an essential step for precise analysis of irradiation experiments. Since naturally occurring isotopes in the sample can influence nuclear reactions, and parameters such as reaction cross-sections and fission yields vary for each isotope, it is necessary to perform isotopic corrections. In this experiment, the ^{232}Th target was prepared by pressing ThO_2 powder with a purity of 99.99%, where the isotopic abundance of ^{232}Th dominates. Therefore, isotopic correction for the thorium sample is not required.

2. Neutron beam fluence fluctuation correction

The neutron beam fluence cannot remain perfectly stable during long irradiation periods. Consequently, the neutron beam injection rate fluctuates to a certain extent and requires correction. The neutron beam fluence fluctuation correction factor K is calculated using Eq. (2):

$$K = \frac{\sum_{i=1}^{n} \Phi_i \left(1 - e^{-\lambda \Delta t_i}\right) e^{-\lambda T_i}}{\Phi \left(1 - e^{-\lambda T}\right)}$$

where n is the number of time intervals into which the irradiation time is divided, Δt_i is the duration of the i-th time interval, T_i is the time interval from the end of the i-th interval to the end of irradiation, T is the total irradiation time, Φ_i is the neutron flux averaged over the sample during Δt_i, and Φ is the neutron flux averaged over the sample during T.

3. Self-absorption correction

In irradiation experiments, self-absorption correction is crucial for ensuring the accuracy and reliability of experimental data. Since experimental samples possess finite thickness, when γ-rays pass through the material they interact with the sample substance, causing a portion of the γ-rays to be absorbed. This results in loss of γ-rays and reduction of intensity, ultimately decreasing the number of γ-rays actually detected and affecting the precision of experimental results. Therefore, to obtain accurate data, correction for the self-absorption effect is necessary. Typically, the self-absorption effect is closely related to the atomic number of the sample material and the energy of the γ-rays. When the sample is thicker or has higher density, the self-absorption effect becomes more pronounced.

Assuming the intensities of the γ-rays before and after passing through the material are I_0 and I, respectively, the following relationship holds:

$$I = I_0 e^{-\mu_m d_m}, \quad \mu_m = \frac{\mu}{\rho}, \quad d_m = d\rho$$

where μ_m is the energy-dependent mass attenuation coefficient (cm^2/g); μ is the linear absorption/attenuation coefficient (cm^{-1}), typically denoted by $N_v\sigma$ (N_v is the atomic number density of the sample and σ is the interaction cross-section between γ-rays and the sample material); ρ denotes the density of the absorbing material (g/cm^3); d_m is the mass thickness of the sample (g/cm^2); and d is the linear thickness of the sample (cm).

According to the attenuation law of γ-rays in matter, the self-absorption correction factor C_s can be calculated as expressed in Eq. (4):

$$C_s = \frac{\mu_m d_m}{1 - e^{-\mu_m d_m}}$$

Values for thorium metal were obtained from the National Institute of Standards & Measurements XCOM database [**?**]. According to the ratio of Th and O, the total mass absorption/attenuation coefficient for different γ-ray energies of Th and O materials could be obtained by interpolation.

4. Coincidence summing correction in γ-ray cascade radiation

In γ-ray spectral analysis, the coincidence summing effect of γ-ray cascade radiation significantly impacts measurement accuracy, necessitating appropriate corrections. Since the time intervals between cascade γ-ray emissions from radionuclides are on the order of 10^{-9} s, while γ-ray spectrometers typically have

resolving times exceeding 10^{-6} s [**?**], coincidence summing occurs when two or more cascade γ-rays are misidentified as a single summed signal in the detector, leading to increase or decrease of the full-energy peak count and thus deviation from the true value. Furthermore, higher detector efficiency leads to more pronounced loss or gain in full-energy peak counts. This effect is particularly noticeable in measurements of radionuclides with complex decay schemes.

Typically, coincidence correction for γ-ray cascades can be divided into two scenarios. In the first scenario, three γ-rays are denoted as γ_{mi}, γ_{ij}, and γ_{jn}, where the four excited states m, i, j, and n follow a sequentially decreasing energy order. The γ-rays γ_{mi}, γ_{ij}, and γ_{jn} represent transitions from higher excited states m, i, and j to lower excited states i, j, and n, respectively. When the cascade decay γ-rays γ_{mi} or γ_{jn} enter the detector simultaneously with the measured γ-ray γ_{ij}, the deposited energy in the detector exceeds E_{ij}, preventing its counting at the full-energy peak position of γ_{ij}. This results in reduction of the full-energy peak count for the measured γ-ray γ_{ij}. Taking the cascade γ-ray γ_{mi} as an example, the coincidence summing factor C_{mi} induced by γ_{mi} relative to the measured γ-ray γ_{ij} can be expressed as shown in Eq. (5):

$$C_{mi} = 1 - h\varepsilon_T$$

where h represents the ratio of the emission probability of the cascade γ-ray γ_{mi} to the sum of the emission probabilities of all γ-rays decaying from the excited state m; ε_T denotes the full spectrum detection efficiency of the cascade γ-ray γ_{mi}.

In the second scenario, when an intermediate energy level n exists between states i and j, a cascade decay may occur where the excited state i decays to the intermediate state n, followed by subsequent decay from state n to state j ($\gamma_{in} \rightarrow \gamma_{nj}$). If the cascade γ-rays γ_{in} and γ_{nj} are simultaneously detected, their summed energy deposition ($E_{ij} = E_{in} + E_{nj}$) contributes to an enhanced count rate at the full-energy peak position of the measured γ-ray γ_{ij}. The coincidence summing correction factor $C_{in,nj}$, introduced by the cascade decay $\gamma_{in} \rightarrow \gamma_{nj}$, can be formulated in Eq. (6):

$$C_{in,nj} = 1 + h\varepsilon_{p,in}\varepsilon_{p,nj}$$

where $\varepsilon_{p,in}$ and $\varepsilon_{p,nj}$ denote the full-energy peak efficiencies of the cascade γ-rays γ_{in} and γ_{nj}, respectively.

The peak-to-total ratio (R_{ij}) is defined as the ratio of the efficiency of the full-energy peak ($\varepsilon_{p,ij}$) to the efficiency of the full spectrum ($\varepsilon_{T,ij}$). R_{ij} remains invariant with variations in the source-to-detector distance and does not require knowledge of the absolute activity of the reference source, expressed mathematically as follows:

$$R_{ij} = \frac{\varepsilon_{p,ij}}{\varepsilon_{T,ij}}$$

The $\varepsilon_{p,ij}$ can be obtained from Fig. 5, and the value of R_{ij} can be calculated using the methodology described in Ref. [**?**]. The $\varepsilon_{T,ij}$ and R_{ij} parameters were used in the coincidence summation correction calculations.

5. Pile-up correction

In irradiation experiments, pile-up effect correction aims to reduce or eliminate measurement errors caused by the detector receiving multiple particles or photons within a short time interval. This phenomenon, also known as pulse pile-up, is particularly significant under high count rates and can degrade energy spectrum resolution and measurement accuracy. The pile-up effect arises due to the finite response time of the detector to sequential events. When two or more events occur within the detector response time, they are superimposed, leading to count loss and resulting in undercounting. Such superposition can also deteriorate energy resolution and induce spurious peaks in the spectrum.

In γ-ray spectrometry measurements, the detected count rate of γ-rays decreases exponentially over time. If the measurement duration is relatively short, the overall count loss rate remains nearly constant, allowing the use of an average count loss rate to correct for the actual count loss in the experiment. As reported in Ref. [**?**], for the nuclide ^{90}Rb with a half-life of 158 s, the systematic error introduced by pile-up correction was only 0.02%. In practice, the longer the half-life of a nuclide, the lower the count loss rate, and the smaller the error caused by pile-up effects. In this experiment, the sample was cooled for more than 0.4 hours, and the detected fission products had relatively long half-lives. Therefore, pile-up correction can be neglected in this case.

The correction factors for dead time correction, neutron beam fluence fluctuation correction, self-absorption correction, and coincidence summing correction in γ-ray cascade radiation, as well as the total correction factor, are summarized in Table 3.

TABLE 3 . The values of correction factors for each identified fission product.

Fission products	Dead time correction	Coincidence summing correction	Self-absorption correction	Neutron fluence fluctuation correction	Total correction factor
^{132}Te					
^{139}Ba					
^{142}La					
^{143}Ce					

C. Uncertainties

After full consideration of uncertainty sources, the main uncertainties in the presented measurements are summarized in Table 4. The cross-section uncertainty (0.77%) of the ^{232}Th(n,f) reaction was obtained by an interpolation method from literature [**?**]. The total uncertainty (3.83%–10.35%) in the present work is the quadratic summation of the given uncertainties.

TABLE 4 . Terms contributing to the uncertainties associated with the yield values.

Fission products	E_c (%)	E_ϵ (%)	E_T (%)	E_I (%)	E_m (%)	E_α (%)	E_n (%)	E_σ (%)	E_{total} (%)
^{132}Te									
^{139}Ba									
^{142}La									
^{143}Ce									

Where E_c is the uncertainty of γ-ray count; E_ϵ is the uncertainty of γ-ray full-energy peak efficiency; E_T is the uncertainty of the half-life; E_I is the absolute intensity of γ-ray; E_m is the uncertainty of sample mass; E_α is the uncertainty of self-absorption; E_n is the uncertainty of neutron flux density; E_σ is the uncertainty of fission cross-section of ^{232}Th(n,f) reaction; E_{total} is the total uncertainty.

D. Results

After careful calculation and correction, the cumulative FPYs for ^{232}Th induced by 2.8 ± 0.3 MeV neutrons and the evaluated cumulative FPY values based on interpolation are presented in Table 5.

TABLE 5 . Terms contributing to the uncertainties associated with the yield values.

Fission products	ENDF/B-VIII.1	JEFF-3.3	JENDL-5	Present work
^{132}Te	7.639$±0.457	6.889±0.713	4.846±0.170	2.385±$0.147
^{139}Ba	4.810$±0.246	5.801±0.506	8.399±0.458	9.143±$0.452
^{142}La	6.382$±$0.245			
^{143}Ce				

As shown in Fig. 8 [Figure 8: see original paper], the present data are displayed along with existing literature data for nine fission products generated from quasi-monoenergetic neutron-induced fission of ^{232}Th, where neutrons were produced

by an accelerator-based source. The red spheroidal dots in Fig. 8 show our results for yields ranging from ^{91}Sr to ^{143}Ce obtained from fission of ^{232}Th with 2.8 MeV neutrons, in comparison to data from H. Naik et al. (left triangle and dots, respectively) [**?**, **?**] and those from P.M. Prajapati et al. at different energies (right triangle) [**?**] and C. Chauvin (inverted triangle) [**?**] at 14 MeV. Typically, the cumulative FPYs vary between approximately 2.385% for ^{132}Te and 9.143% for ^{142}La. Our data support the negative slope of the energy dependence previously observed for high-yield fission products ^{91}Sr, ^{92}Sr, ^{97}Zr, ^{135}I, ^{139}Ba, and ^{142}La. The situation for ^{132}Te, ^{133}I, and ^{143}Ce is uncertain. Although previous data [**?**, **?**] suggest no energy dependence for ^{132}Te down to below 2.8 MeV, a comparatively lower value was observed in our experiments relative to prior data. For the high-yield fission product ^{133}I, our datum is consistent with the trend of previous data [**?**, **?**], which indicate a positive slope. Data in energy regions as low as below 2.8 MeV are not available for ^{133}I to draw further conclusions.

All raw data described in this paper have been uploaded to the Science Data Bank. A direct link to the dataset is available at https://doi.org/xxxxxx.

Fig. 8 [Figure 8: see original paper]. Energy dependence of cumulative fission product yields obtained in fission of ^{232}Th with monoenergetic neutrons.

IV. Technical Validation

The comparison between the present experimental measurement data and evaluated data is shown in Fig. 9 [Figure 9: see original paper]. The model for fission yield calculation used in TALYS-1.96 [**?**] is the Okumura model (read in yields and excitation energies) [**?**, **?**]. The cumulative FPYs from evaluated nuclear data libraries ENDF/B-VIII.I, JEFF-3.3, and JENDL-5 are interpolated from nine cumulative FPYs corresponding to adjacent energies (0.4 MeV or 0.5 MeV and 14 MeV) in ENDF [**?**]. The yields of ^{139}Ba and ^{142}La are significantly higher than the evaluated yield values from the databases. It is postulated that this phenomenon is due to the relatively short half-life of the resultant nuclide. Therefore, it is crucial to optimize the irradiation, cooling, and measurement times. Grouping samples based on the half-lives of product nuclides for tailored irradiation, cooling, and measurement is necessary to fill gaps in experimental data across different energy regions.

Fig. 9 [Figure 9: see original paper]. Present data compared to the cumulative FPYs from evaluated nuclear data.

V. Usage Notes

The cumulative FPYs measurements for 2.8 MeV quasi-monoenergetic neutron-induced fission of ^{232}Th are reported, based on experiments conducted on the CPNG-600 Cockcroft-Walton accelerator at CIAE. Herein, we detail the data analysis procedures and ensure open access to the cumulative FPY data, intending to support both nuclear physics specialists and scientists in adjacent

disciplines for their future research.

This dataset possesses significant utility across various domains of nuclear physics, particularly in:

(1) **Nuclear model validation and reactor design:** The experimental results can effectively verify the accuracy of nuclear models used to calculate cumulative yields of nuclear reactions and provide data references for establishing yield databases in the CENDL library. After reactor shutdown, radioactive decay of fission products continues to generate significant heat, known as decay heat. If not adequately removed, this can lead to core meltdown. Fission product yield data serve as the fundamental basis for calculating the magnitude of this decay heat. This data provides safety engineers with essential information to determine required cooling capacity and duration after shutdown, forming the lifeline for nuclear safety system design.

(2) **Nuclear waste treatment and transmutation research:** The management of long-lived radioactive waste, such as minor actinides, from nuclear reactors is a global challenge. Transmutation, which converts long-lived nuclides into short-lived or stable ones through nuclear reactions, is a promising solution. In this context, the yield of ^{97}Zr as a fission product is a key parameter for assessing transmutation process efficiency and product toxicity. By quantifying ^{97}Zr production within transmutation targets, scientists can validate theoretical models and optimize system designs.

(3) **Test reactor accident analysis:** The decay of ^{132}Te produces ^{132}I, a radionuclide known for its intense gamma rays and high volatility, making it readily detectable in the environment. Consequently, elevated levels of ^{132}I detected after a nuclear accident strongly indicate ^{132}Te release. Analyzing the activity and ratio of ^{132}Te/^{132}I provides critical information for experts to reconstruct accident timelines, estimate release inventory, and determine the time of fission occurrence.

(4) **Environmental and geochemical studies:** The yield data can be applied to investigate sorption and migration behavior in environmental and geochemistry studies. The environmental behavior of lanthanides is of great interest. For instance, utilizing the yield of ^{142}La can serve as a tracer to study the sorption, desorption, and migration of lanthanum in soils, sediments, and water bodies. This research is crucial for understanding the environmental geochemical cycle of rare earth elements and assessing the safety of geological disposal of radioactive nuclides.

(5) **Radioisotope production:** A further critical application of fission yield data is its role as a production roadmap in radioisotope manufacturing. Given that numerous radioisotopes are vital for medical, industrial, and research applications, yield data are fundamental for selecting the most efficient production method. They allow direct comparison of yields across various reaction channels, thereby guiding scientists toward the most eco-

nomical and efficient pathway that offers the highest yield with minimal impurities.

VI. Code Availability

The theoretical simulations for this published dataset were performed using software based on TALYS version 1.96. TALYS, developed under the leadership of Koning at the Nuclear Research and consultancy Group (NRG), is a comprehensive nuclear reaction code built upon key theoretical models such as the optical model, the Hauser–Feshbach statistical theory with width fluctuation corrections, the two-component exciton model, and the coupled-channels approach. The code is capable of simulating a wide range of nuclear reactions induced by various incident particles—including neutrons, protons, deuterons, tritons, He-3 and alpha particles, and photons—over an extensive energy range (0.001–200 MeV) and for mass numbers spanning $12 < A < 339$. It provides predictions for cross-sections, energy spectra, and fission fragment mass distributions, among other observables. Notably, TALYS demonstrates excellent agreement with experimental data in reproducing fission fragment mass distributions. Owing to these capabilities, the TALYS code has been selected as the theoretical tool for the present work.

In computing fission product mass yields, the fission product mass yield curve is determined for neutrons on ^{232}Th at incident energies of 2.8 MeV. The parameters listed above represent a minimum input file for TALYS [**?**]. Other parameters were manually specified. The fymodel 4 (model for calculation of fission yields) was adopted for the Okumura model; the ffmodel 1 (model for distribution of fission fragments) was employed in the GEF model, with fission fragments generated by Ali Al-Adili and Fredrik Nordstroem; the ldmodel 5 (model for level densities) was chosen for Gogny-Hartree-Fock-Bogoluybov level densities from numerical tables. A bin size of 100 (the number of excitation energy bins in which the continuum of the initial compound nucleus is divided for further decay) was selected. More detailed information related to the data analysis code can be accessed as a notebook in the Science Data Bank, where the complete dataset for this study has been uploaded. A direct link to the dataset is available at https://doi.org/xxxxxx.

Acknowledgements

The authors thank Xianlin Yang for fruitful discussions. The authors are grateful to the staff of the CPNG-600 Cockcroft-Walton accelerator at the Institute of Nuclear Physics, China Institute of Atomic Energy (CIAE), for their excellent operation of the neutron generator and other support during the experiment. This work is supported in part by the Continuous Support Basic Scientific Research Project (Grant No. BJ010261223282).

Author Contributions Statement

Bo Gao was responsible for methodology, software, conceptualization, and writing—reviewing and editing. Chang-lin Lan was involved in data curation, investigation, and writing—original draft. Bo Xie carried out formal analysis. Gong Jiang and Jia-hao Wang assisted with measurement and methodology. Yan-liang Chang, Kuo-zhi Xu, and Jiang-long Pan performed measurements. Yu-ting Wei and Xiao-dong Pan participated in editing and English grammar correction. Yang-bo Nie, Shi-long Liu, Xi-chao Ruan, Yi Yang, and Ke-liang Shi took part in writing—reviewing and editing. All authors reviewed the manuscript.

Declarations

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Z. Ren, Y. Yang, Y. Chen et al., Measurement of the ^{232}Th(n, f) cross section in the 1-200 MeV range at the CSNS Back-n. Nucl. Sci. Technol. 34, 115 (2023). doi: 10.1007/s41365-023-

[2] Z. Chen, Recent progress in nuclear data measurement for IMP. Nucl. Sci. Technol. 28, 184 (2017). doi: ADS at 10.1007/s41365-017-0335-3.

[3] L. ChangLin, X. BaoLin, Z. Kai et al., Measurement of ^{232}Th(n, 2n)^{231}Th reaction cross-sections at neutron energies of 14.1 MeV and 14.8 MeV using neutron activation method. Nucl. Sci. Technol. 26, 100 (2015). doi: 10.13538/j.1001-8042/nst.26.060501.

[4] Shilong Liu, Yi Yang, Jing Feng, et al., Fission Product Yields Measurement of ^{232}Th Induced by 14.8 MeV Neutron, Atomic Energy Sci. Technol. 47, 901-906 (2013). doi: 10.7538/yzk.2013.47.06.0901.

[5] K. M. Broom, 2.95-MeV and 14.8 MeV neutron-induced fission of ^{232}Th, Phys. Rev. C 133, B874-B883 (1964). doi: 10.1103/PhysRev.133.B874.

[6] D.L. Swindle, D.T. Moore, J.N. Beck et al., Mass Distribution of 3 MeV Neutron Induced Fission of ^{232}Th, J. Inorg. Nucl. Chem. 33, 3643-3647 (1971). doi: 10.1016/0022-1902(71)80268-3.

[7] A. Turkevich and J. B. Niday, Radiochemical Studies on the Fission of ^{232}Th with Pile Neutrons. Nucl. Sci. Technol. Phys. Rev 84, 52-60 (1951). doi: 10.1103/PhysRev.84.52.

[8] H. N. Erten, A. Grütter, E. Rössler et al., Mass Distribution in the Reactor-Neutron-Induced Fission of Thorium-232. Nucl. Sci. Technol. Nuclear Science and Engineering 79, 167-174 (1981). doi: 10.13182/NSE81-A27405.

[9] A. E. Richardson, H. L. Wright, J. L. Meason et al., Mass Distribution in the Fission of ^{232}Th by Degraded-Fission-Spectrum Neutrons. Nucl. Sci. Eng. Nucl. Sci. Technol. 94, 413-425 (1986). doi: 10.13182/NSE86-A18351.

[10] Yujie Ge, Changlin Lan, Huiyi lv et al., Measurement of Cumulative fission product yields on ^{235}U induced by 2.8 MeV neutrons. Appl. Radiat. Isotopes 200, 110907 (2023). doi: 10.1016/j.apradiso.2023.110907.

[11] Yuting Wei, Lan, Changlin Lan, Li Feng et al., Determination of the half-life of ^{91}Sr in uranium sample bombarded by 14.8 MeV neutron. Radiat. Detect. Technol. Methods Nucl. Sci. Technol. 6, 361–366 (2022). doi: 10.1007/s41605-022-00332-

[12] Xianlin Yang, Changlin Lan, Yangbo Nie et al., Cumulative fission yield measurements with 14.7 MeV neutrons on ^{238}U. Chin. Phys. C Nucl. Sci. Technol. 47, 024001 (2023). doi: 10.1088/1674-1137/aca1ab.

[13] M.E. Gooden, C.W. Arnold, J.A. Becker et al., Energy Dependence of Fission Product Yields from ^{235}U, ^{238}U and ^{239}Pu for Incident Neutron Energies Between 0.5 and 14.8 MeV. Nucl. Data Sheets 311, 319-356 (2016). doi: 10.1016/j.nds.2015.12.006.

[14] National Institute of Standards and Technology. https://physics.nist.gov/.

[15] Xiaoxiang Jin, Chaofeng Chen, Guan Lin et al., Study on Method of Coincidence Summing Correction in γ-ray Cascade Radiation. Atomic Energy Sci. Technol. 51, 1077-1083 (2017). doi: 10.7538/yzk.2017.51.06.1077.

[16] Xiaobing Luo, Yijun Xia and Xiangguan Long, Co-incidence summing corrections in the measurement of gamma-rays intensity. Nucl. Tech. 7, 428-435 (1992). doi: CNKI:SUN:HJSU.0.1992-07-009.

[17] Yi Yang, Experimental research on the dependence of ^{235}U fission yields on incident neutron energies. China Institute of Atomic Energy (2005).

[18] A.D. Carlson, V.G. Pronyaev, D.L. Smith et al., International Evaluation of Neutron Cross Section Standards. Nucl. Data Sheets 110, 3215-3324 (2009). doi: 10.1016/j.nds.2009.11.001.

[19] H. Naik, R. Crasta, S.V Suryanarayana et al., Mass distribution in the quasi-mono-energetic neutron-induced fission of ^{232}Th. Eur. Phys. J. A 50, 144 (2014). doi: 10.1140/epja/i2014-14144-

[20] H. Naik, Sadhana Mukherji, S.V. Suryanarayana et al., Measurement of fission products yields in the quasi-mono-energetic neutron-induced fission of ^{232}Th. Nucl. Phys. A 952, 100-120 (2016). doi: 10.1016/j.nuclphysa.2016.04.003.

[21] P. M. Prajapati, H. Naik, S. Mukherjee et al., Fission Product Yield in the Neutron-Induced Fission of ^{232}Th with Average Energies of 5.42, 7.75, and 10.09 MeV. Nucl. Sci. Eng. 176, 106–113 (2014). doi: 10.13182/NSE12-78.

[22] C. Chauvin, Measurement of several yields at fission by 14-MeV neutrons and by reactor neutrons. Grenoble, France,

[23] H. Naik, G. N. Kim, K. Kim et al., Mass yield distributions in the ^{232}Th (n,f) reaction with fast neutrons. Phys. Rev. C 100, 014606 (2019). doi: 10.1103/PhysRevC.100.014606.

[24] Tongyu Sun, Wenxin Li, Tianrong Dong et al., Mass Distribution in the 14.7 MeV Neutron-Induced Fission of ^{232}Th. High Energy Phys. and Nucl. Phys. 12, 221-228 (1988). doi: c208e8c7-6cd6-4c65-8897-837c130d369c.

[25] J. Blachot, P. Cavallini and C. Chauvin, Fission yield measurements in the 14 MeV fission of ^{232}Th, ^{233}U, ^{238}U by direct gamma spectrometry analysis. Chemical Nuclear Data Measurements and Applications (1971). doi: 10.1680/CNDMAA.44555.0003.

[26] J. Blachot, L. C. Carraz, P. Cavallini et al., Analyse par spectrometrie gamma directe des produits de fission de ^{235}U. J. Radioanal. Chem. 7, 309–317 (1971). doi: 10.1007/BF02513802.

[27] S. Okumura, T. Kawano, P. Jaffke et al., ^{235}U(n, f) Independent fission product yield and isomeric ratio calculated with the statistical Hauser–Feshbach theory. J. Nucl. Sci. Tech. 55, 1009–1023 (2018). doi: 10.1080/00223131.2018.1467288.

[28] A.J. Koning, S. Hilaire and S. Goriely, TALYS: modeling of nuclear reactions. Eur. Phys. J. A 59, 131 (2023). doi: 10.1140/epja/s10050-023-01034-3.

[29] A.J. Koning, D. Rochman, JJ.-Ch. Sublet et al., TENDL: Complete Nuclear Data Library for Innovative Nuclear Science and Technology. Nucl. Data Sheets 155, 1-55 (2019). doi: 10.1016/j.nds.2019.01.002.

[30] B. Zhang, X. Ma, K. Hu et al., Performance of the CENDL-3.2 and other major neutron data libraries for criticality calculations. Nucl. Sci. Technol. 33, 8 (2022). doi: 10.1007/s41365-

Note: Figure translations are in progress. See original paper for figures.