Prediction of prompt neutron spectra of the photon induced reactions on ^{238}U and ^{232}Th at incident energies from 4 and 22 MeV

Anabella Tudora[1)], Dan Filipescu[2)], Ioana Gheorghe[2)]

[1)]University of Bucharest, Faculty of Physics, [2)]Institute for Nuclear Physics and Engineering Horia Hulubei, Bucharest-Magurele, Romania

The recent experimental investigations of photon-induced reactions on ^{238}U and ^{232}Th performed at the **NewSUBARU laser Compton-scattering γ-ray source** have brought the need for reliable predictions of photo-fission prompt neutron spectra. The measurements made use of a high-and-flat neutron efficiency detection system originally designed for (γ,xn) photo-neutron reactions with typical evaporation neutron emission spectra up to 5 MeV. Dedicated predictions of prompt neutron spectra of photon-induced fission reactions will enable the neutron detection efficiency characterization for realistic fission spectra extending well above the (γ,xn) photo-neutron energy range.

Unfortunately such prompt neutron spectra cannot be calculated in the frame of refined prompt emission models (e.g. FIFRELIN, CGMF, PbP, DSE, HF^{3}D etc.) because any information concerning the fission fragment distributions Y(A,TKE) (necessary as input in these models) is missing in the case of photo-fission of actinides. Experimental data of prompt emission for ^{238}U(γ,f) and ^{232}Th(γ,f) are missing, too. So that the validation of model results (by their comparison with experimental data) is impossible.

Consequently the only way remains **the prediction** of prompt neutron spectra for ^{238}U(γ,f) and ^{232}Th(γ,f) by using **a most probable fragmentation approach with input parameters provided by recent systematics**. At higher incident photon energies, where multiple fission chances are involved, the fission chance probabilities (necessary in the prompt emission calculations mentioned above), which are expressed as fission cross-section ratios, are based on the results of nuclear reaction codes (such as EMPIRE, TALYS, GNASH).

Calculation of prompt neutron spectra in the photo-fission of ^{238}U and ^{232}Th

$$N(E) = N_{FF}(E) + N_{prefiss}(E)$$

Sum of total spectrum of **prompt neutrons emitted by fission fragments** (FF) and of **pre-fission neutrons** (emitted by each CN prior to fission,) in the case of multiple fission chances (indexed i).

$$N_{prefiss}(E) = \sum_{i=2}^{n} PF_i \sum_{j=1}^{i-1} \varphi_{ev\,j}(E) \Big/ <\nu>_{tot}$$

$$N_{FF}(E) = \sum_{i=1}^{n} PF_i <\nu_i> N_i(E) \Big/ <\nu>_{tot}$$

$$<\nu>_{tot} = <\nu>_{FF} + <\nu>_{prefiss}$$

$$<\nu>_{FF} = \sum_{i=1}^{n} PF_i <\nu_i> \Big/ \sum_{i=1}^{n} PF_i$$

$$<\nu>_{prefiss} = \sum_{i=1}^{n}(i-1)PF_i \Big/ \sum_{i=1}^{n} PF_i$$

$$PF_x = RF_x = \frac{\sigma_{\gamma,xnf}}{\sigma_{\gamma,F}} \qquad \sigma_{\gamma,F} = \sum_{x=1}^{n} \sigma_{\gamma,xnf}$$

Fission cross section ratios (TALYS, EMPIRE, GNASH)

Prompt emission from FF – most probable fragmentation approach with inclusion of sequential neutron emission from complementary light and heavy fragments of the most probable fragmentation of each CN undergoing fission (each fission chance). *(A.Tudora Eur.Phys.J.A 56 (6) (2020) rt.no.168)*

$$\Phi_k(\varepsilon) = \int_0^{T_{max\,k}} \varphi_k(\varepsilon,T) P_k(T)\, dT$$

energy spectrum, in the center-of-mass frame, corresponding to each prompt neutron (indexed k) emitted from a fission fragment (LF or HF) of the most probable fragmentation

$$P_k^{(L,H)}(T) = \begin{cases} \dfrac{2T}{(T_{max\,k}^{(L,H)})^2} & T \le T_{max\,k}^{(L,H)} \\ 0 & T > T_{max\,k}^{(L,H)} \end{cases}$$

residual temperature distribution corresponding to each emission sequence (triangular form with a sharp cut-off) *A.Tudora, F.-J.Hambash, V.Tobosaru, Eur.Phys.J.A 54 (2018) 87*

$$T_{max\,k}^{(L,H)} = \frac{3}{2} <T_k>_{L,H} \qquad <T_k>_{L,H} = r_k^{(L,H)} <T_i>_{L,H} \qquad T_{max\,k}^{L,H} = \frac{3}{2} r_k^{(L,H)} <T_i>_{L,H}$$

according to the systematic of residual temperature ratios based on detailed sequential emission calculations (*A.Tudora, Eur.Phys.J.A 56 (3) (2020) art.no.84*)

$r_{k=1}^{(L,H)}$=0.7, $r_{k=2}^{(L,H)}$=0.5, $r_{k=3}^{(L)}$=0.42, $r_{k=3}^{(H)}$=0.36, $r_{k=4}^{(L)}$=0.38, $r_{k=4}^{(H)}$=0.28, etc. and $r_{L,H}$ = 0.6 (all emission sequences)

$<T_i>_{L,H}$: average temperature of **initial fragments** (before prompt emission) → systematic of input parameters for the most probable fragmentation approach (LA model) with or without sequential emission (*A.Tudora, Eur.Phys.J.A 56 (9) (2020) 225*)

$$\Phi_k^{(L,H)}(\varepsilon) = \int_0^{T_{max\,k}^{(L,H)}} P_k^{(L,H)}(T)\, \varphi_k^{(L,H)}(\varepsilon)\, dT = \varepsilon\, \sigma_{c\,L,H}^{(k)}(\varepsilon) \int_0^{T_{max\,k}^{(L,H)}} K_k^{(L,H)}(T)\, P_k^{(L,H)}(T) \exp(-\varepsilon/T)\, dT$$

$$N_k^{(L,H)}(E) = \int_{(\sqrt{E}-\sqrt{E_{f\,L,H}})^2}^{(\sqrt{E}+\sqrt{E_{f\,L,H}})^2} \frac{\Phi_k^{(L,H)}(\varepsilon)\, d\varepsilon}{4\sqrt{E_{f\,L,H}\,\varepsilon}}$$

$$K_k^{(L,H)}(T) = \left(\int_0^{\infty} \varepsilon\, \sigma_{c\,L,H}^{(k)}(\varepsilon) \exp(-\varepsilon/T)\, d\varepsilon \right)^{-1}$$

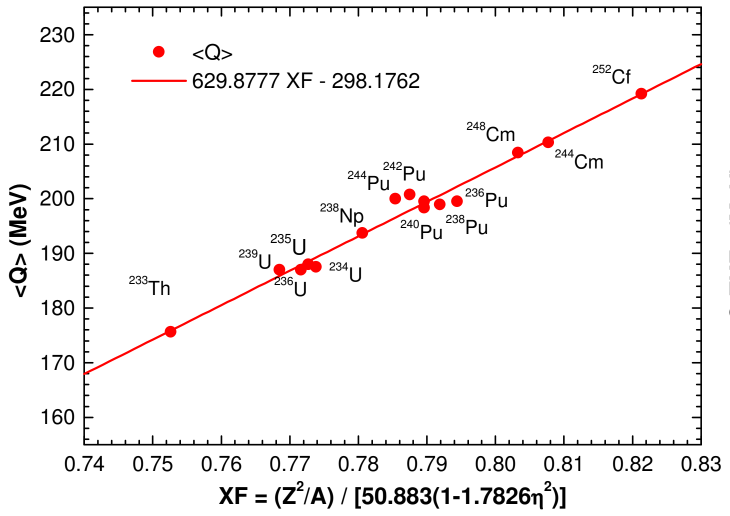
Input parameters of the most probable fragmentation approach (LA model) with or without sequential emission → **<TXE>** and **$<T_i>_{L,H}$** corresponding to each compound nucleus undergoing fission at a given incident photon energy.

Because any experimental information regarding both the fission fragments and the prompt emission quantities of the fissioning nuclei ^{238}U and ^{232}Th is completely missing, the only way to obtain these input parameters remains the use of a **recent systematic** reported in Ref. *A.Tudora, Eur.Phys.J.A 56 (9) (2020) art.no.225*

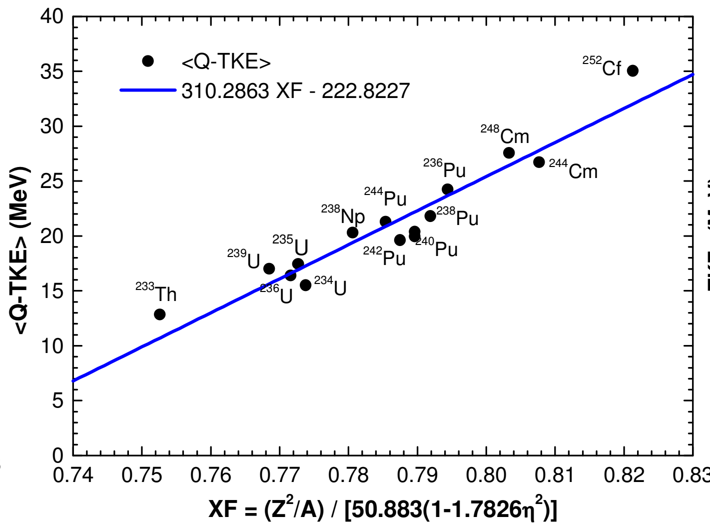
I. <TXE> of each fissioning nucleus – using systematics

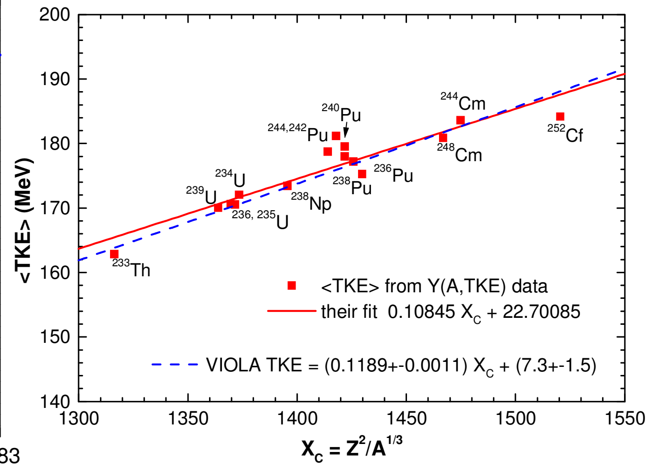
$$<TXE> = <Q>(XF) + E^* - <TKE>_{Viola} \quad \text{or} \quad <TXE> = <Q-TKE>(XF) + E^*$$

in which **<Q>(XF)** is given by the systematic

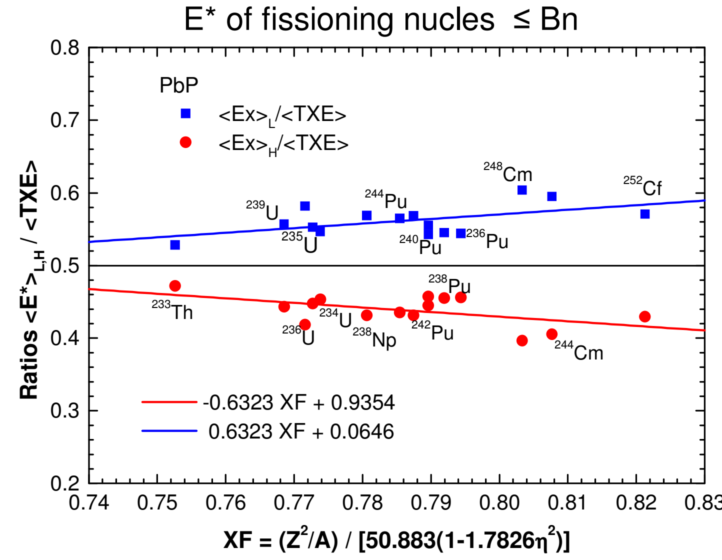


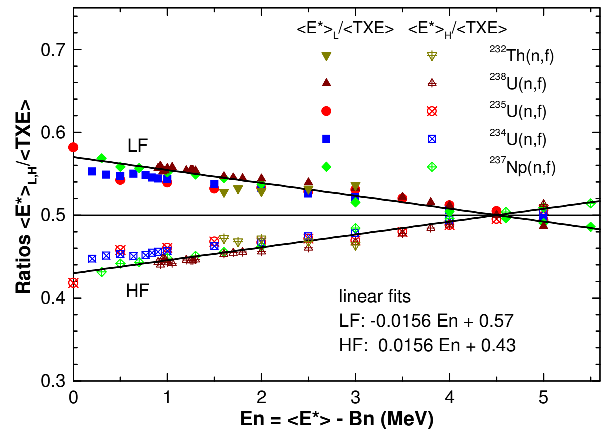
in which **<Q–TKE>(XF)** is given by the systematic



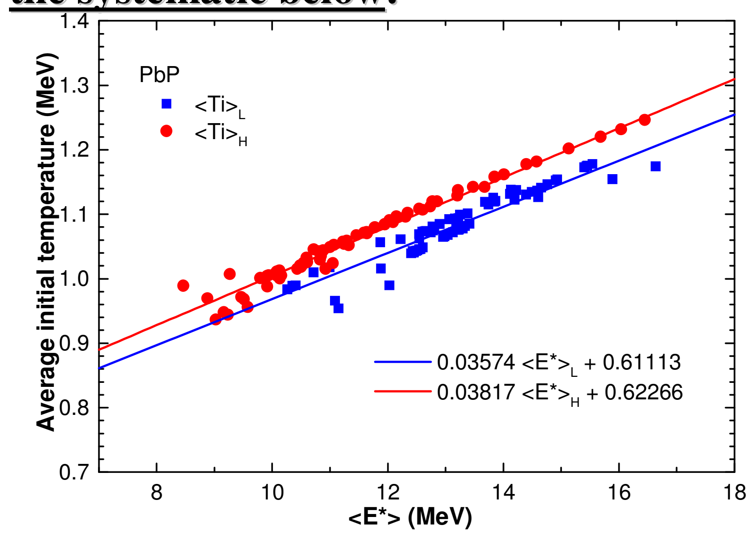


II. Once <TXE> is calculated, $<E^*>_{L,H}$ corresponding to all fissioning nuclei (main and secondary chances) are obtained



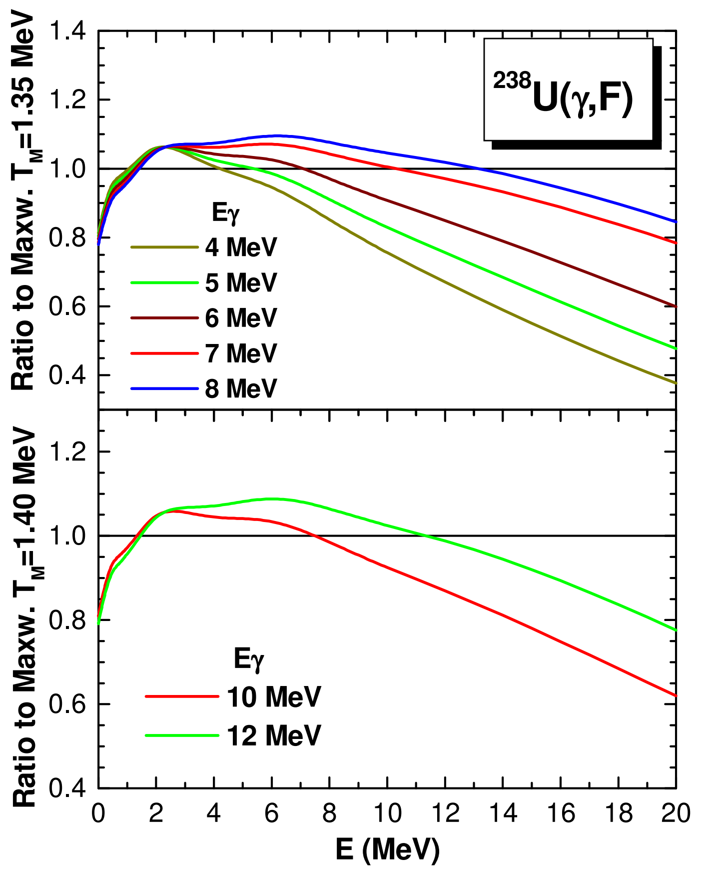


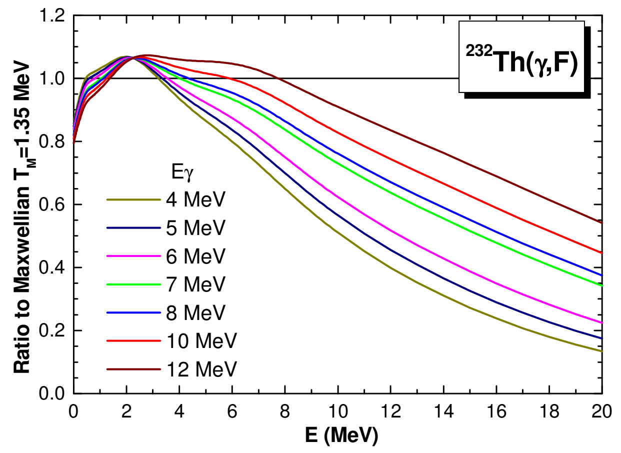
III. Using the determined $<E^*>_{L,H}$ the average initial temperatures $<T_i>_{L,H}$ are obtained from the systematic below:



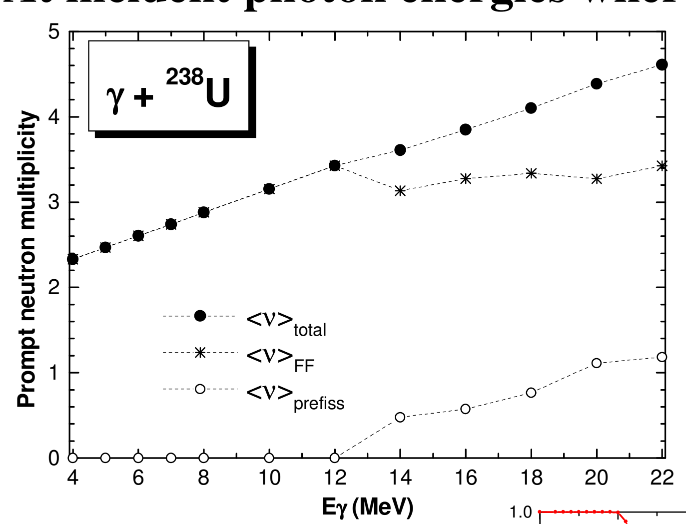
Preliminary predicted results

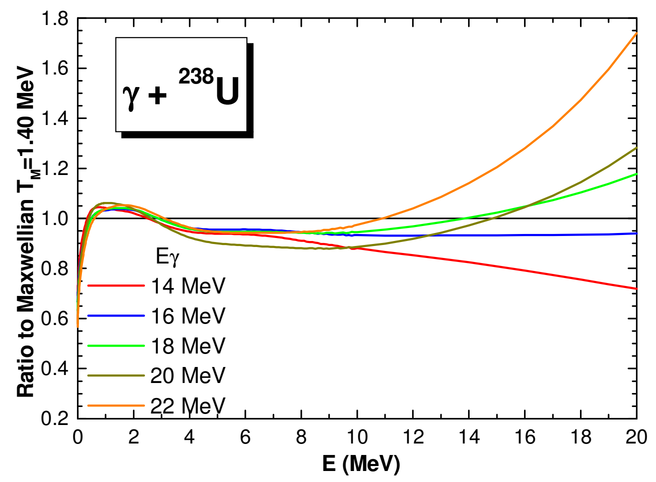
At incident photon energies where only one fission chance is involved (up to 12 MeV)



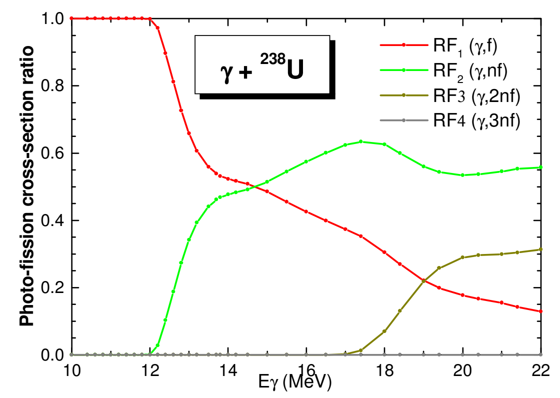


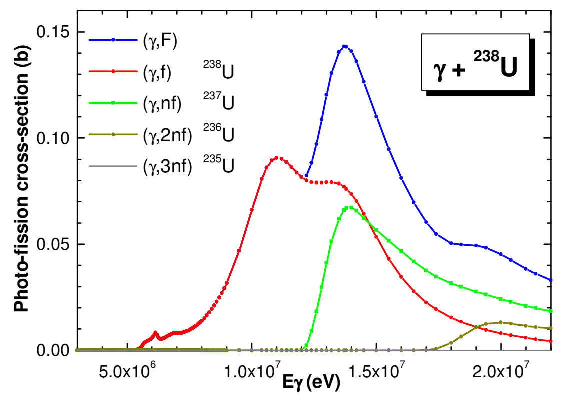
At incident photon energies where multiple fission chance are involved





Using the fission probabilities expressed as photo-fission cross-section ratios which were obtained from **EMPIRE calculations** using the input parameters of *Sin et al. Phys.Rev.C 103 (2021) 054605.*





The present prediction of prompt neutron spectra of the photon-induced reactions on the ^{238}U and ^{232}Th targets in the energy range 4 – 22 MeV is based on the following reliable models and systematics:

1) The spectra of prompt neutrons emitted by FF are provided by the most employed and well validated **approach of most probable fragmentation**, i.e. the LA model, which can be used either in the **classical version** of *Madland and Kahler, Nucl.Phys.A 957 (2017) 289*, or in the **new version including the sequential emission** (*Tudora, Eur.Phys.J.A 56 (2020) 25*). The **input parameters <TXE> and $<T_i>_{L,H}$** of whatever of these LA model versions (with or without sequential emission) are provided by **a recent systematic** (which vas validated by the good description of all experimental data of prompt neutron spectrum by the results of both LA model versions with and without sequential emission, *Tudora, Eur.Phys.J.A 56 (2020) 225*).

2) The pre-fission neutron spectra are based on **fission probabilities** (expressed as **fission cross-section ratios**) obtained from the **EMPIRE calculations** of γ + ^{238}U and γ + ^{232}Th reactions using the **input parameters** of *Sin et al. Phys.Rev.C 103 (2021) 054605*.

So that the predicted prompt neutron spectra are expected to be successfully used in the processing of experimental data obtained from the photo-fission and photo-neutron reactions on ^{238}U and ^{232}Th investigated by quasi-monochromatic γ-ray beams produced in Laser Compton scattering at the NewSUBARU synchrotron radiation facility.

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