ISTC PROJECT B-404
"ACTINIDE NUCLEAR DATA EVALUATION"
Neutron data for U-Th fuel cycle
Report to the WPEC Meeting,
Coronado/San Diego/USA
May 12-14, 2003

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Abstract

Consistent evaluation of ^{238}U, ^{234}U, ^{232}U and ^{232}Th measured data base is performed from a few keV up to 20 MeV. ^{233}U data evaluation from 0.6 keV up to 20 MeV is under way. Hauser-Feshbach-Moldauer theory, coupled channel model and double-humped fission barrier model are employed. Total, differential scattering, fission and (n,xn) data are consistently reproduced as a major constraint for inelastic scattering cross section estimate. The direct excitation of ground state and higher band levels is calculated within rigid rotator and soft (deformable) rotator model, respectively. Sructures evident in ^{238}U and ^{232}Th measured neutron emission spectra are correlated with excitation of levels of $K^{\pi} = 0^-$ and $K^{\pi} = 0^+, 2^+$ banbs. Available prompt fission neutron spectra data are described. Average resonance parameters are provided, which reproduce evaluated cross sections for neutron energies up to ~150 keV (~40 keV in case of ^{233}U).

This work is performed under the Project Agreement B-404 of JINER with the International Science and Technology Center (Moscow). The Financing Party for the Project is Japan.

1 Introduction

Nuclear data of ^{238}U, especially capture and inelastic scattering processes in ^{238}U are a source of controversy long since. The consistency of available data was addressed by NEA NSC Working Party on International Evaluation Cooperation Subroup 4. We investigated the possibility of reproducing average capture cross section data trend in a statistical model of compound nucleus reactions in unresolved resonance range (URR) and fast neutron energy range. Above URR, as distinct from the previous evaluations of ^{238}U data, we proceed within full-scale Hauser-Feshbach theory, coupled channel optical model and double-humped fission barrier model, avoiding any arbitrary normalizations to the measured data. We "tuned" the model in case of ^{238}U, validated it in case of ^{232}Th, and will apply for ^{232}U, ^{234}U, ^{233}U, ^{231}Pa and ^{233}Pa data evaluation.

During the period from 01.10.2000 till 15.05.2003 nuclear data files for **^{238}U, ^{232}Th, ^{234}U and ^{232}U** were compiled. Unresolved resonance parameters, smooth cross sections, neutron angular distributions and secondary neutron spectra were evaluated. For ^{232}U updated Reich-Moore resonance parameters are provided. URR energy region was extended up to ~150 keV.

^{238}U, ^{232}Th, ^{234}U and ^{232}U target nuclides differ, at least, in two major aspects. First, collective level structures, except levels of ground state band, are strongly different. Second, fissilities of target and other nuclides, emerging after emission of 1, 2, 3 or 4 neutrons, are different. Consequently, contributions of fission chances to the observed fission cross sections, as well as prompt fission neutron spectra, also would be much different. Both peculiarities would influence compound and direct components of neutron emission spectra.

2 Model

Consistent description of total, elastic, fission and capture cross section data provides an independent estimate of inelastic scattering cross section from threshold up to 20 MeV for ^{238}U and ^{232}Th target nuclides. The important item for the inelastic scattering cross section in a few MeV incident neutron energy range is the compound scattering to the continuum levels and direct excitation of rotational and vibrational levels of target nucleus. For compound scattering fission data fit served as a major constraint. In case of ^{234}U and ^{232}U target nuclides it was the only constraint.

The direct excitation of ground state rotational band levels 0^+-2^+-4^+-6^+-8^+ is estimated within rigid rotator model. To calculate the direct excitation cross sections for $\beta(\gamma)$-vibration ($K^\pi = 0_2^+, 0_3^+, 2^+$) as well as octupole ($K^\pi = 0^-$) band levels a soft rotator model was used. Major soft rotator model parameters were fixed by consistent description of ^{238}U inelastic scattering data for $E_n \lesssim 3.5$ MeV and collective level structure for excitations up to $\sim$2.5 MeV. Levels of negative parity band K^{π}=0^- are defined by octupole deformation parameter β_3 and parameter of softness to the octupole vibrations μ_{β_3}. Values of β_3-parameter are defined by fitting neutron angular distribution data, level positions are kept unaffected by varying softness parameter μ_{β_3}. Experimental inelastic cross section data (Plompen et al., 2000) for excitation of groups of octupole band levels of ^{238}U up to $\sim$ 3 MeV allow to define β_3- and $\mu_{\beta_3}-$parameter values. We adopted these β_3- and $\mu_{\beta_3}-$parameter values for other nuclides. Other model parameters - the scaling factor $h\omega_0$, μ_{β_2} and μ_{γ} softness parameters to quadrupole longitudinal and transversal vibrations, respectively, and non-axiality parameter γ_0, were obtained by fitting positions of K^{π} $=0_2^+$, 0_3^+, K^{π} $\simeq 2^+$ band heads for specific nuclides.

Second peculiarity is pronounced in fission observables. Multiple-chance fission structure is obtained by consistent description of ^{238}U(n,f) (^{232}Th(n,f)) and ^{238}U(n,xn) (^{232}Th(n,xn)) reaction cross sections. Analysis of measured ^{238}U(n,f) and ^{232}Th(n,f) PFNS data showed that a number of data peculiarities could be correlated with the influence of (n,$x$nf) pre-fission neutron spectra on the observed prompt fission neutron spectra, neutron spectra from fission fragments being described with Watt distributions. Variation of Watt equation energy parameter - CMS energy per nucleon, allowed to describe PFNS data shapes for emitted prompt fission neutron energies $\varepsilon \gtrsim 0.5$ MeV. The increase of the cut-off energy $E_{th} \sim E_n - B_f$ of (n,nf) reaction neutron spectra with increase of excitation energy of fissioning nucleus is reproduced for E_n $\sim$13-18 MeV. A step-like irregularities around emitted neutron energy ε $\sim$3 -5 MeV for E_n above (n,2nf) reaction threshold are correlated with first neutron spectrum of ^{238}U(n,2nf) (^{232}Th(n,2nf)) reaction. We demonstrated that correct estimates of fission chances, pre-fission (n,$x$nf) reaction spectra, alongside with simple modelling of spectra of neutrons, emitted from fission fragments, allow to reproduce a number of peculiarities in measured prompt fission neutron spectra. Present approach provides a versatile theoretical tool for measured PFNS data analysis for target nuclides with various fissilities.

3 ^{238}U

The advantage of present evaluation of URP is that it provides average energy dependent parameters which reproduce ^{238}U evaluated cross sections using conventional ENDF/B processing codes [1].

We demonstrated that consistent description of inelastic scattering data reproduces measured neutron emission spectra. Since measured neutron emission spectra are inclusive both of elastic, inelastic and prompt fission neutron spectra (PFNS), detailed description of measured PFNS data for first- and multiple-chance fission is obtained for E_n up to 18 MeV. We demonstrated here that one needs the sophistication of direct scattering model, level density modelling and PFNS representation to describe consistently the available measured data base for ^{238}U [2, 3, 4, 5, 6].

4 ^{232}Th

Present calculations fairly describe available data base on ^{232}Th+n total, elastic, fission, capture, inelastic scattering, (n,2n), prompt fission neutron spectra and neutron emission spectra [3, 7].

A systematic discrepancy of excitation functions of discrete levels data obtained by (n,n') time-of-flight method (Ciarcia et al., 1985) and by (n,n'γ) measurements (Dave et al., 1985) is well known. In most cases calculated cross sections for excitation of discrete levels and group of levels of γ-vibration $K^\pi = 0^+$, β-vibration $K^\pi = 0^+$, anomalous rotational $K^\pi = 2^+$ bands as well as first octupole $K^\pi = 0^-$ band levels are in nice agreement with (n,n') method measured data up to ~3 MeV. Measured data derived by (n,n'γ) method were supposed in most cases overestimate inelastic scattering cross section above E_n ~1.5 MeV and underestimate it at lower energies, or in the whole energy range, in a number of cases. This conclusion, made by Ciarcia et. al. (1985), was never supported by the detailed statistical nuclear reaction model calculations. Present investigation, taking into account direct excitation of γ-vibration $K^\pi = 0^+$, β-vibration $K^\pi = 0^+$ and anomalous rotational $K^\pi = 2^+$ bands levels, seems to be the first trial.

For incident neutron energy up to E_n ~150 keV capture cross section is defined mainly by radiation strength function $S_{\gamma 0}$ value. For $E_n \gtrsim 150$ keV calculated cross section is rather sensitive to the radiation strength function $S_{\gamma 0}$ energy dependence and inelastic scattering competition, since fission channel competition is rather weak. Radiation strength function $S_{\gamma 0}$ energy dependence is defined, to a large extent, by the level density of ^{233}Th at low excitation energies, i.e., below three-quasiparticle excitation threshold. For still higher incident neutron energies $E_n \gtrsim 1$ MeV, the (n,γn$'$) reaction competition to the "true" capture (n,$\gamma\gamma$) reaction cross section is rather strong, it essentially defines the capture cross section drop above E_n ~1 MeV. The competition of (n,γf) reaction to the "true" capture (n,$\gamma\gamma$) reaction is inessential for ^{232}Th(n,$\gamma\gamma$) reaction due to low fission probability of ^{233}Th nuclide [8].

Average resonance parameters were obtained which reproduce total, capture and inelastic cross sections from 4 keV up to 150 keV. Double-differential neutron emission cross sections are shown to be consistent with present estimate of inelastic neutron scattering to the discrete and continuum levels [3, 9]. Consistent estimates of fission cross section data and prompt fission neutron spectra above emissive fission threshold give direct evidence of pre-fission (n,nf) reaction neutron influence on the observed PFNS [5].

We assume that for incident neutron energy range of 4 keV - 20 MeV the reliability of present evaluated data file might be comparable with that of ^{238}U data file.

5 ^{234}U

We applied approach, validated in case of ^{232}Th(n,γ) and ^{238}U(n,γ) reactions for ^{234}U(n,γ) reaction cross section estimation. We adopted $s-$wave radiative strength function $S_{\gamma 0} = 22.81\times10^{-4}$ ($\Gamma_\gamma = 26$ meV and $\langle D_{l=0}\rangle = 11.4$ eV). The $s-$wave radiative strength function estimate of $S_{\gamma 0} = 35.09\times10^{-4}$ ($\Gamma_\gamma = 40$ meV and $\langle D_{l=0}\rangle = 11.4$ eV) produces higher capture cross section, notwithstanding the scatter of measured capture data by Muradyan et al. (2000), lower value of radiative strength function seems to be more justified. The pattern of $s-,p-$and $d-$wave channel contributions to the capture cross section in the energy range of 1.5 - 140 keV is also rather similar to that of ^{232}Th or ^{238}U target nuclides. Some differences might be attributed to the increased fission competition in $p-$ and $d-$wave entrance channels. Competition of (n,γf) reaction to capture reaction is not that essential as it would be in case of ^{232}U(n,γ) reaction. The competition of (n,γn') reaction to the "true" capture (n,$\gamma\gamma$) reaction is essential above $E_n \sim$1 MeV. The important peculiarity of the calculated ^{238}U(n,γ) capture cross section - Wigner cusp above first excited level threshold, is also pronounced in case of ^{234}U(n,γ) reaction cross section. Another capture cross section drop is observed around ~0.8 MeV. It might be correlated with the strong increase of compound inelastic scattering competition due to vibrational levels of $K^\pi = 0_2^+, K^\pi = 0_3^+$, $K = 0^-$ and $K^\pi \simeq 2^+$ bands. Above $E_n \sim$1 MeV capture cross section decrease is defined by (n,γf) and (n,γn') reactions competition. Previous evaluated capture cross sections are drastically discrepant with present calculation at $E_n \gtrsim$100 keV. Some consistency is observed only with ENDF/B-VI up to ~15 keV. A consistent description of the most complete set of measured data on the (n,γ), (n,f) and (n,n') reaction cross sections for the ^{238}U and ^{232}Th target nuclides enables one to consider the statistical theory estimates of ^{234}U(n,γ) reaction as fairly realistic [10].

Lumped contribution of direct excitation of ground state band levels, octupole K^π=0^- and K^π=2^- bands, quadrupole longitudinal β-vibration $K^\pi = 0_2^+$, transversal $\gamma-$vibration $K^\pi = 0_3^+$ and anomalous rotation band $K^\pi = 2^+$ levels is shown to attain ~20% of total inelastic cross section at $E_n \gtrsim 2$ MeV.

Quadrupole longitudinal β-vibration $K^\pi = 0^+$ band levels and quadrupole transversal $\gamma-$vibration K^π= 0^+ band levels are defined by softness parameters to respective vibrations μ_{β_2} and μ_γ. Anomalous rotational $K^\pi \simeq 2^+$ $\gamma-$band levels are defined by non-axiality parameter γ_o, which is correlated with positions of $K^\pi \simeq 2^+$ levels in ^{238}U,^{234}U, ^{232}U and ^{232}Th. In case of ^{234}U, levels of second $K^\pi = 0^+_2$ band are classified as quadrupole longitudinal $\beta-$vibrations. Position of this $K^\pi = 0^+$ $\beta-$vibration band-head is lower than in case of ^{238}U, but higher than in case of ^{232}U nuclide. As regards the position of quadrupole transversal vibrations K^π=0^+_3 band, it lies much higher than in case of ^{238}U, but lower than in case of ^{232}U. In other words, ^{234}U turns out to be less soft to γ-vibrations, than ^{238}U, but more soft than ^{232}U. These peculiarities might be correlated with positions of anomalous rotational band K^π =2^+ in ^{232}U, ^{234}U and ^{238}U, here ^{234}U band again occupies intermediate position, as compared with ^{238}U and ^{232}U nuclides. Anomalous rotational $K^\pi \simeq 2^+$ band level positions are defined by non-axiality parameter γ_0.

6 ^{232}U

^{232}U target nuclide undergoes substantial thermal neutron fission and exhibits a non-threshold behavior at low incident neutron energies in contrast with the other even-even U targets. Neutrons with incident energies up to ~200 eV excite in ^{232}U only one spin state, so Reich-Moore resonance parameters, fitting total and fission data could be obtained much more easily than in case of even-odd target. We demonstrated how Reich-Moore parameter set, corresponding to two fission channels, proposed in BNL-325, could be modified to improve fit of measured total and fission data. Improved fission data description in the valleys between resonances was obtained changing the character of interference between resonances [11, 12].

We reconciled the data by Auchampaugh et al. in keV-energy region with data by Fursov et al. at higher energies using statistical model calculation. Fission threshold is not observed in the reaction ^{232}U(n,f), nonetheless we argue that step-like irregularity in fission cross section around ~1 MeV incident neutron energy also might be attributed to the step in the level density of fissioning nuclide. In the domain of emissive fission rather different contribution of (n,$x$nf) reactions for the ^{232}U(n,f) reaction, than in case of ^{238}U(n,f) reaction, is observed. Relative contribution of ^{232}U (n,nf) reaction is lower than in case of ^{238}U(n,nf) reaction for $E_n \lesssim 9$ MeV, but much higher for $E_n \gtrsim 9$ MeV. These peculiarities are attributed to the high ^{232}U target nuclide fissility with neutrons and consequent high non-emissive fission contribution to the observed fission cross section.

We adopted $s-$wave radiative strength function $S_{\gamma 0} = 84.8\times10^{-4}$ (Γ_γ = 40 meV and $\langle D_{l=0}\rangle$ = 4.717 eV). The important peculiarity of the calculated ^{238}U(n,γ) capture cross section, Wigner cusp above first excited level threshold, is not that pronounced as in case of lower fissility targets. The pattern of $s-, p-$ and $d-$wave channel contributions to the capture cross section is also rather different from that of ^{238}U, ^{234}U or ^{232}Th target nuclides. The $p-$wave contribution is higher than that of $s-$wave only above ~30 keV, while that of $d-$wave neutrons is the lowest. In case of ^{238}U(n,γ) reaction main contribution comes from $p-$wave neutrons above 5 keV, while that of $d-$wave neutrons becomes higher than that of $s-$wave above ~130 keV. These peculiarities might be attributed to the increased fission competition in $p-$ and $d-$wave entrance channels. Competition of (n,γf) reaction to capture reaction is also essential [12].

Lumped contribution of direct excitation of ground state band levels, octupole, β-vibration and anomalous rotation band levels is shown to attain ~50% of total inelastic cross section at $E_n \gtrsim 2$ MeV. The differences of present and previous estimates of total inelastic scattering cross sections are defined by rather large relative direct inelastic scattering contribution, which almost doubles inelastic scattering cross section in a few MeV incident neutron energy range [13].

7 Conclusions

^{238}U, ^{232}Th, ^{232}U and ^{234}U data files are available on WWW of Nuclear Data Section of International Atomic Energy Agency (**http://www-nds.iaea.org**). Detailed reports are published as INDC Reports by NDS of IAEA [2, 7, 10, 13]. For ^{238}U, ^{232}Th and ^{232}U secondary neutron spectra were calculated with Weiscopf -Ewing model, new versions of evaluated data files are compiled, where secondary neutron spectra, like in case of ^{234}U, are calculated with Hauser-Feshbach theory. They would be available in a while.

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