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ABSTRACT

The production cross section of the 984-keV γ-rays from the ^{48}Ti(n,n′) reaction has been evaluated from 2 MeV up to 16 MeV. For this purpose all currently available measured discrete γ-ray production and partial neutron inelastic cross sections including their uncertainties from the reaction threshold up to ≈ 20 MeV were collected, thoroughly analysed, corrected and renormalized to the updated standards when it was necessary and possible. The non-model evaluation of the excitation function and covariance matrix was performed by the least squares code GMA. Finally, the ^{48}Ti(n,n′γ_{984keV}) cross section is recommended as a reference in the energy interval from 2.8 to 16 MeV where minimal fluctuations are observed and uncertainties do not exceed ≈ 5%. Combination of this reaction with the standard ^{10}B(n,$\alpha_1\gamma_{478keV}$) and reference ^{7}Li(n,n′γ_{478keV}) cross sections covers the full energy range pertinent to fission and fusion applications.

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1. Introduction

The nuclear reaction standards [1] still do not have a neutron-induced prompt discrete γ-ray production cross section, that can be used as a reference for the measurement of other (n,xγ) reactions in a wide energy range. An exception is the reaction $^{10}B(n,\alpha_1\gamma_{478keV})$ which is a standard below 1 MeV and thus can be used for such a purpose. However, as a non-threshold reaction it is more sensitive to the low energy neutrons or to the background at nuclear facilities. This makes difficult its use in the fast energy range.

To solve this problem, the threshold discrete γ-ray production reactions on Li, Ti, Fe and other nuclei were considered as potential candidates [2] - [4].

Recently the $^{7}Li(n,n'\gamma_{478keV})$ reaction was shown to be an appropriate reference from 0.9 to 8 MeV [1], [5]. Based on 12 experiments available in this energy range, its cross section was evaluated with an uncertainty ≈ 2% by the least squares code GMA [6], [7].

The use of the reaction $^{56}Fe(n,n'\gamma_{847keV})$ as a reference has the problem of a large 847-keV γ-ray background produced in iron often massively present in experimental set-ups. In addition, the competing reaction $^{56}Fe(n,p)$ generates ^{56}Mn, which after β^- decay to ^{56}Fe, emits the same 847-keV γ-rays.

The (n,n'γ) reaction on Ti, like Fe, has a large cross section fairly constant over a wide incident neutron energy range. The main isotope ^{48}Ti has a large natural abundance 73.72% (others: ^{49}Ti - 5.41%, ^{50}Ti - 5.18%, ^{47}Ti - 7.44%, ^{46}Ti - 8.25%). Additionally, high-purity titanium is easily available, relatively cheap and not difficult to prepare as uniform density samples with appropriate thickness. Ti is generally not present in large quantities in experimental venues.

Due to these properties, the $^{48}Ti(n,n'\gamma)$ and $^{49}Ti(n,2n\gamma)$ reactions are considered as potential candidates for a γ-ray reference. A preliminary evaluation of the $^{48}Ti(n,n'\gamma_{984keV})$ cross section was reported in 2012 [8]. The report also recommends additional and independent measurements for establishing this reaction as a reference. Following this request, new precise measurements were recently carried out at JRC Geel [9], [10], and at LANSCE [11], [12].

This report collects and analyses all existing measurements and describes the non-model evaluation of the $^{48}Ti(n,n'\gamma)$ cross section in energy interval 2 – 16 MeV. At the end it shows that in combination with the reactions $^{10}B(n,\alpha_1\gamma_{478keV})$ and $^{7}Li(n,n'\gamma_{478keV})$ this may be the best way to provide a discrete γ-ray reference for covering the energy range relevant for fission and fusion applications.

2. Experimental data

All known and available measurements of neutron-induced discrete γ-ray production and inelastic scattering cross sections relevant for $^{48}Ti(n,n'\gamma_{984})$ cross section evaluation are summarised in Table 1. The EXFOR database [13] served as a source of numerical information and references. Since 1965 there are thirteen independent measurements of the 984-keV γ-ray yield and six measurements of the partial inelastic neutron scattering cross sections populating the first excited and other levels of ^{48}Ti. Among them only two experiments have used enriched ^{48}Ti samples.

Next, four subsections consider the cross sections measured by detection of either discrete γ-rays or discrete (partial) inelastic scattered neutrons, angular distribution of the 984-keV γ-rays and intercomparison of available data. We focused on details of measurements, applied corrections and reported uncertainties which impact on the evaluation process. *Additional corrections we applied to the original experimental data or our decision to exclude the particular data sets are highlighted by italic font*.

TABLE 1. KNOWN MEASUREMENTS OF THE $(n,n'\gamma_{984})$ AND (n,n_1) CROSS SECTIONS ON ISOTOPE ^{48}Ti OR ELEMENTAL Ti.

Author, Reference	Year Lab	Neutron Energies and Resolution	Sample	Method, γ-Detector, Resolution and Angles	Corrections applied and Absolute normalization	EXFOR Entry
Registration of the discrete γ-rays from the (n,n′γ) reaction						
D.L. Broder et al. [15]	1965 IPPE	1.1 - 3.2 MeV ΔE = 35 - 80 keV	^{nat}Ti	NaI, ΔE_γ = 11 keV; 20° - 125°	multiple scat.of *n* and *γ* in sample; relative to $^{56}Fe(n,n'\gamma_{847})$	40035.011
F.C. Engesser et al. [18], [19]	1965-67 Naval	2.8, 14.7 MeV ΔE = 35 - 80 keV	^{nat}Ti	NaI, <90° ± 20°>	corrected for *γ*-ray self absorption; relative to $^{32}S(n,p)$	14325.009 11531.013
A.P. Arya et al. [21]	1967 W.Virginia	14.3 MeV	^{nat}Ti	NaI, 90°	relative to ^{27}Al foil activation	11521.003
W. Breunlich et al. [22]	1971 IRK	14.4 ± 0.3 MeV ΔE = 35 - 80 keV	^{nat}Ti	TOF; Ge <40° - 88°>	corrected for *n*- and *γ*-scattering and $^{49}Ti(n,2n\gamma)$; relative to $^{27}Al(n,\alpha)$	21286.003
U. Abbondanno et al. [24]	1973 INFN	14.2 ± 0.16 MeV ΔE = 35 - 80 keV	^{nat}Ti	TOF; 2 NaI(Tl), ΔE_γ =84 keV, 30° - 150°	corrected for *γ*-self absorption abs norm. by associated α-particles	20493.014
E. Konobeevskij et al. [26]	1973 FIAN	1.0 – 1.23 MeV, ΔE = 17 keV (thin)	^{nat}Ti	Ge(Li), ΔE =4.0 keV	corrected for *n*- and *γ*-scattering;	40213.004
		1.0 – 1.49 MeV, ΔE = 38 keV (thick)	^{nat}Ti	Ge(Li), ΔE =4.0 keV	relative to $^{56}Fe(n,n'\gamma_{847})$	40213.003
J.K. Dickens [27]	1974 ORNL	4.9, 5.4, 5.9 MeV ΔE = 150 - 200 keV	^{nat}Ti ^{48}Ti	TOF; Ge(Li), 55° and 125°	mult. scat. of *n* and γ in sample; n-flux - by NE-213 detector	10426.002 10426.004
K.A. Connell et al. [28]	1975 Aston	14.2 MeV ΔE = 30 keV	^{nat}Ti	TOF; NaI, ΔE_γ =86 keV, <78° ~ 92°>	multiple scattering in sample; counting α associated T(d,n)	20866.007
A.I. Lashuk et al. [16], [17]	1994 IPPE	0.9 - 7.36, 15 - 16 MeV ΔE = 30 keV	^{nat}Ti	Ge(Li), ΔEγ =4.5 keV, ~ 90°	mult. scat. in sample and γ angular; relat. to $^{56}Fe(n,n'\gamma_{847})$ and $^{56}Fe(n,p)$	41186.007 41186.027
Yu.Ya. Nefedov et al. [29]	2000 Sarov	14.3 MeV	^{nat}Ti	TOF; NaI(Tl) at 125°	multiple scattering in sample; α associated T(d,n) and p-telescope	41379.005

TABLE 1. *(CONT.)*

Author, Reference	Year Lab	Neutron Energies and Resolution	Sample	Method, n-Detector, Resolution and Angles	Corrections applied and Absolute normalization	EXFOR Entry
			Registration of the discrete γ-rays from the (n,n′γ) reaction			
D. Dashdorj et al. [31], [32]	2007 LANL	1.0 - 240 MeV, ΔE = 9 keV - 37 MeV	^{48}Ti	TOF; HPGe, 27° - 142°	multiple scattering in sample; relative to ^{238}U(n,f)	14162.002
A. Olacel et al. [9]	2015 JRC	0.92 – 17.0 MeV, ΔE = 9 keV - 37 MeV	^{nat}Ti	TOF; 10 HPGe, 110° and 150°	multiple scattering in sample; relative to ^{235}U(n,f)	23346.007
R.O. Nelson et al. [12], [11]	2018 LANL	1.0 - 77 MeV, ΔE = 7 keV – 4.3 MeV	^{nat}Ti	TOF; HPGe, 27° - 142°	γ attenuation in sample; relative to ^{7}Li(n,n'γ_{478}); ^{56}Fe(n,n'γ_{847})	personal communic.
			Registration of inelastically scattered neutrons from the (n,n_1) reaction			
M.B. Pasechnik et al. [34]	1969 Kiev	2.9 MeV	^{nat}Ti	TOF, stilbene scintillator 30 - 135°	multiple scattering in sample; relative to H(n,n)	40045.006
E. Barnard et al. [35]	1974 ANL	1.277 - 1.487 MeV "broad" ΔE ≈ 20 keV	^{nat}Ti	TOF 25° - 155°	multiple scattering in sample;	10048.086
	1974 Pelindaba	1.070 - 1.500 MeV "good" ΔE ≈ 5 – 10 keV	^{nat}Ti	TOF 90°	relative to C(n,$n_{elastic}$)	10048.089
E. Almen-Ramström [36]	1975 Studsvik	2.0 - 3.25 MeV ΔE = 0.1 – 0.2 MeV	^{nat}Ti (889+983 keV)	TOF, NE scintillator 125°	multiple scattering in sample; relative to H(n,n)	20788.029
I.A. Korzh et al. [37]	1977 Kiev	1.5, 2.0, 2.5, 3.0 MeV 50 keV	^{nat}Ti	TOF, Stilbene 20° - 150°	multiple scattering in sample; relative to H(n,n)	40531.115 40532.016
W.E. Kinney et al. [38]	1977 ORNL	4.07 - 8.56 MeV ΔE = 60 - 70 keV	^{nat}Ti	TOF, NE-213 15° - 140°	multiple scattering in sample; relative to H(n,n)	10285.019 10285.031
A. Smith et al. [39]	1978 ANL	1.5 - 4.5 MeV ΔE = 25 - 50 keV	^{nat}Ti	TOF, Scintillator 20° - 160°	multiple scattering in sample; relative to H(n,n)	10669.004

2.1 Cross sections measured by detection of discrete 984-keV γ-rays.

The first measurements of the discrete gamma rays from Titanium have been carried out at the end of 1950s at IPPE by A. Androsenko, D. Broder and co-workers [14]. They have used a D(d,n) neutron source to produce 3 MeV neutrons, a ring Ti sample and a NaI detector to register γ-rays. In the following experiments the incident neutron energies were extended with the help of the T(p,n) and T(d,n) reactions, a Ge(Li) detector was employed to detect discrete γ-rays with higher energy resolution [15]. Corrections for multiple neutron scattering and attenuation of gammas in the sample were applied. The absolute normalization was obtained using the cross-section value (0.53 ± 0.02) b for the $^{56}Fe(n,n'_{847})$ reaction at a neutron energy of 1.2 MeV. This method was additionally confirmed by measuring the $^{56}Fe(n,p)$ reaction. The uncertainty in determination of cross sections was rather large ≈ 15%. *We have renormalized the results of measurements carried out at IPPE to the contemporary value 0.47 b of monitoring reaction $^{56}Fe(n,n'_{847})$ which was taken from ENDF/B-VIII.0. Additionally the cross section reported for natural titanium was divided by 0.7372 to convert to the ^{48}Ti target.*

A.I. Lashuk and co-workers from IPPE have measured long time the formation of the discrete gamma rays in inelastic neutron scattering on many nuclei, in particular on Ti. The experiments have started in 1972 [16], the paper summarising all measured cross sections was published in 1994 [17]. Fast neutrons with energy 0.1 -7.47 MeV were produced in the T(p,n) and D(d,n) reactions, 15.4 – 16.3 MeV – T(d,n). Ring samples were mounted around neutron production target, Ge(Li) detector was shielded from the source neutrons by the lead cone. Absolute value of the cross sections was found from comparison with the yield of the 846-keV γ-rays from ^{56}Fe at 1.2 MeV. This procedure was proved by additional measurements of the $^{56}Fe(n,p)$ reaction. The cross sections were corrected for the absorption and multiple scattering in samples, internal conversion, apparatus dead time, etc. *We have renormalized Lashuk's data to the new value of the $^{56}Fe(n,n'\gamma_{846keV})$ cross section similarly as for Broder's data.*

F.C. Engesser and W.E. Thompson have presented in 1965 - 1967 measurements of prompt γ-rays from the interaction of fast neutrons with natural Ti. The 2.8 MeV incident neutrons were produced from D(d,n) and 14.7 MeV from the T(d, n) reactions by a 150-keV deuteron beam impinging on a thick, water-cooled titanium tritide target [18], [19]. The scattering sample was in the form of a right circular cylinder 7.6 cm long and 35.6 cm in diameter. Gamma rays from the scattering sample reached the NaI detector, located at 90° to the line of the incident neutron beam, through a collimator in the shield. The $^{32}S(n,p)^{32}P$ cross section was used to determine the neutron flux. The reported data were corrected for the self-absorption of γ-rays. The total uncertainty was estimated as 10-15%. *After renormalization to the actual $^{32}S(n,p)^{32}P$ cross section given in dosimetry file IRDFF-1.05 [20] and correction for the γ-ray angular anisotropy, we still see that Engesser and Thompson data at both energies are systematically higher than others. Due to this reason, as well as because of a too massive sample and large uncertainties we disregarded the measurements of Engesser and Thompson in the present evaluation.*

A.P. Arya and co-workers in 1967 have measured the angular differential cross section at 90 degree for the $^{48}Ti(n,n'\gamma_{984keV})^{48}Ti$ reaction at 14.3 MeV using a NaI(Tl) detector [21]. The published information about this experiment is insufficient. The reported cross section, being converted to the angle-integrated one, notably disagrees with other measurements. *Due to this we excluded Arya's data from the present evaluation.*

W. Breunlich et al. in 1970 have measured the discrete γ-ray production cross section from Ti at 14.4 MeV [22]. Gammas, separated from neutrons by the time of flight technique (TOF), were registered by a Ge detector. The experimental set-up has defined an effective angle subtended by the detector from 40 to 88 degrees. The authors have shown by theoretical modelling that multiplying of the angle-averaged cross section by 4π will correctly estimate the integrated reaction cross section. The experimental data were corrected for multiple scattering and attenuation of neutrons and γ-rays in the sample. The authors have estimated the contribution of 984-keV γ-rays from the $^{49}Ti(n,2n)^{48}Ti$ reaction as equal to (59 ± 12) mb and subtracted it from total measured yield. The absolute value was obtained relative to the $^{27}Al(n,\alpha)$ reaction cross section (117.0 ± 0.8) mb at 14.43 MeV taken from [23]. *This* *agrees with the reference value (116.45 ± 0.45) mb recommended by the latest version of the dosimetry library IRDFF-1.05 [20]. It worth noting that the authors have given the total uncertainty 13.2% as 3 standard deviations. We reduced it to 2 standard deviations to be more consistent with other measured data.*

W. Abbondanno and co-workers have performed in 1973 measurements of the differential cross-sections for the production of the 0.99 and l.31 MeV γ-rays from natural Ti for an incident neutron energy of 14.2 MeV [24]. The sample used was a right circular cylinder 6 cm diameter and 12 cm long. The γ-rays were detected by means of two NaI(Tl) detectors surrounded by large lead shields. The discrimination between gammas and neutrons was performed by means of the TOF technique. The associated-particle technique was used for absolute cross section normalization. No correction was made to take the absorption and the multiple scattering of neutrons in the sample into account, since these effects were assumed to balance each other. This point was checked by performing measurements with samples of different sizes. The γ-ray loss in the sample was taken into account by calculation of the absorption coefficient. The errors attached to the experimental cross-section were estimated, resulting in a total ≈10%. The authors have measured the angular distribution of 984-keV γ-rays at 9 angles between 30 and 150 degrees and obtained the Legendre coefficients. *From these coefficients we found a ratio $\sigma(n,n'\gamma) / (4\pi * d\sigma(n,n'\gamma 90^o)/d\Omega) = 1.236$, which specifies the angular anisotropy (see Section 2.3) and was used for correction of the data of Engesser and Arya. We corrected Abbodanno's data for the contribution from the $^{49}Ti(n,2n\gamma_{984keV})$ reaction which was taken from TENDL-2017 [25].*

E.S. Konobeevskii et al. have measured the 984-keV γ-ray yield from the ^{48}Ti(n,n') reaction above threshold up to 1.23 -1.49 MeV [26]. Neutrons were produced by the T(p,n) reaction and the experiment was carried out with two TiT targets having different thickness: thin – protons lost 17 keV and thick – 38 keV. The circular metallic samples were fabricated from the mixture of Ti and Fe, outgoing γ-rays were recorded by a Ge(Li) counter at 135 degrees. The authors derived the Ti cross section using a reference cross section of (0.17 ± 0.02) mb for the ^{56}Fe(n,n'γ_{847}) reaction averaged in the interval 875 - 900 keV. The latter was measured by authors in a dedicated experiment with a pure Fe sample. The uncertainty of procedure linking relative Ti/Fe and absolute Fe measurements did not exceed 5%. The counting statistics were about 5%.

J.K. Dickens has measured yields for many γ-rays from samples made of natural titanium and enriched in the isotopes ^{46}Ti and ^{48}Ti [27]. Pulsed neutrons with mean energies of 4.9, 5.4 and 5.9 MeV were produced by the D(d,n)^{3}He reaction. The number of neutrons impinging on the sample was measured by a NE-213 scintillation detector with a calculated efficiency. This means that measured (n,n'γ) cross section were not normalized to any other data. The method of the absolute normalization was additionally checked by measuring the C(n,$n_{elastic}$) and ^{27}Al(n,α)^{24}Na reactions. The emitted γ-rays were detected by a Ge(Li) detector at angles of either 55 or 125 degrees. The cross section total uncertainty ≈ 10% resulted from: beam monitoring 7.5%, detector efficiency 5%, corrections for finite geometry and multiple scattering ≈ 2% and counting statistics ≈ 2%.

K.A. Connell and A.J. Cox have measured the γ-rays associated with the ^{48}Ti(n,n'γ) reaction at 14.2 MeV [28]. The gammas were detected at several angles from 0^o to 90^o by a shielded and moveable NaI(T1) detector placed at a distance of 1.39 m from natural Ti sample. Time-of-flight techniques were used for both differentiation between γ-rays and neutrons and reduction of background. The α-particles associated with the neutron generating reaction T(d,n)^{4}He were detected by a NE-102 plastic scintillator sheet that determined the incident neutron flux. The multiple neutron scattering and γ-ray absorption in the sample were accounted for. The authors have fitted the measured angular distribution of the γ-rays by a Legendre polynomial series and derived the integrated cross section. The authors have declared an uncertainty between 3 and 10%. *We have subtracted from the $^{48}Ti(n,n'\gamma)$ data reported by Connell the value 0.0544/0.7372 * $^{49}Ti(n,2n\gamma_{984})$, where the $^{49}Ti(n,2n\gamma_{984})$ cross section was taken from TENDL-2017 [25].*

Yu.Ya. Nefedov et al. have reported in the year 2000 the measurement of the γ-rays from the ^{nat}Ti(n,n'γ) reaction at 14.3 MeV [29], [30]. They used a 15 cm diameter by l0 cm long crystal of Nal(Tl) located behind a concrete wall and the time-of-flight technique. The neutron yield from the target was determined by two scintillation α-counters installed in the deuteron drift tube, which recorded α-particles accompanying the $T(d,n)^4He$ reaction and by a certified proton telescope that replaced the sample. The uncertainties include: determination of the neutron source yield ± 3%; number of primary collisions of neutrons with nuclei of the sample ± 4.5%; contribution of multiple neutron and γ-ray interactions ± 5%; the number of detected γ-rays in the energy interval obtained by unfolding of the pulse height distribution ± 5%. The total methodical error of integral gamma-ray production cross sections is estimated as 9% for the confidence probability of 0.95. *Regrettably in the EXFOR data base the numerical data of this experiment are presented as a gamma spectrum integrated over 0.75 - 1.00 MeV bin. This makes difficult separating the 984-keV γ-ray cross section from all others. Due to this reason the measurements of Nefedov et al. were excluded from the present evaluation.*

D. Dashdorj et al., in the year 2007, have measured the prompt γ-ray production cross sections from an enriched ^{48}Ti sample from 1 to 200 MeV at the Los Alamos Neutron Science Center (LANSCE) spallation neutron source facility of the Los Alamos National Laboratory [31], [32]. The event neutron energies were determined by the time-of-flight technique. The γ-rays were detected with a Compton-suppressed array of HPGe detectors. The γ-ray excitation functions were converted to absolute partial cross sections using the $^{238}U(n,f)$ cross sections. The fission events were counted from a fission chamber located upstream of the ^{48}Ti sample. The necessary corrections were evaluated by Monte Carlo simulations and applied to the raw data. R. Nelson has recently revised the normalization [12], [11] of these measurements based on corrected fission foil thickness data, and will revise the data reported by D. Dashdorj in 2007. The systematic uncertainties in this measurement were about 5%.

R. Nelson et al., in 2015, have measured simultaneously the γ-rays from the first excited states of ^7Li, ^{48}Ti, and ^{56}Fe in the same experiment using the time-of-flight technique with GEANIE [11] at LANSCE. From the ratios of the yields of the γ-ray peaks and using previous cross section measurements, two measurements of the $^{nat}Ti(n,n'\gamma_{948})$ cross section were obtained. In addition, the ratio data and known cross sections are used to check for consistency of all of the cross sections.

The $Ti(n,n'\gamma_{948})$ cross section was determined for $E_n > 1$ MeV from a relative measurement to $^{nat}Fe(n,n'\gamma)$ using $Fe(n,n'\gamma)$ cross sections measured at LANSCE previously. The recently revised $^{nat}Fe(n,n'\gamma_{847keV})$ data, 0.882*EXFOR 14118002 and 0.882*EXFOR 13884002, were used. The two Fe measurements made with different samples, detectors and flight paths were averaged to reduce statistical and systematic uncertainties at energies where both were available. Being a relative measurement, the cross section depends only on the measurement of the sample areal densities, the relative efficiencies for the different gamma-ray energies, the γ-ray angular distributions and on the accuracy of the separately measured Fe cross section.

Similarly, the $Ti(n,n_1'\gamma)$ cross section was determined for $E_n > 1$ MeV from a relative measurement to $^{nat}Li(n,n_1'\gamma)$, but in this case using the recent $^7Li(n,n_1'\gamma_{478keV})$ cross section evaluation [5] to calculate the cross section. Reasonable consistency between all cross sections was observed using the newly normalized Fe and Ti data. With the old normalizations the Li cross sections were not consistent within errors with the Fe and Ti data. The cause of these inconsistencies remains to be resolved.

In both cases the data were corrected for angular distribution (AD) effects in Fe where the evaluation [43] was used (no AD data were available for Ti), photon attenuation in the samples (using MCNP6), and ~1% of the neutron flux that did not strike the disk of the LiF sample. The cross section normalization is accurate to ≈ 3.5%, for the Fe cross section and about 2% for the Li evaluation. The statistical errors are about 3% between 3 and 10 MeV.

The new Nelson measured data were corrected for contributions from the $^{49}Ti(n,2n)$ reaction. They were used in the present fit as shape data since their absolute values are systematically lower than other measurements and lack of angular distribution data make corrections unreliable. The two $^{48}Ti(n,n'\gamma_{948})$ data sets derived from measurements relative to $^{nat}Fe(n,n'\gamma_{847keV})$ and $^{nat}Li(n,n'\gamma_{478keV})$ were used in the fit as two partially correlated subsets of one experiment.

A. Olacel et al. have measured the discrete γ-rays production cross section from the ^{nat}Ti(n,n'γ) reaction at the time of flight facility GELINA (Geel) [9], [10]. The sample was positioned at the flight path 198.7 m from the neutron source. The GAINS HPGe detector array was used to detect the γ-rays at 110^o, 125^o and 150^o. The incident neutron flux was measured by a ^{235}U fission chamber. The experimental cross section was corrected for multiple scattering and attenuation of neutrons and gammas in the sample. The data compiled in EXFOR represent the ^{48}Ti(n,xγ_{984keV}) cross section. *However, the authors did not subtract the contribution from the ^{49}Ti(n,2n) reaction which populates the 984-keV excited state of ^{48}Ti above neutron energy 9.314 MeV. To apply such a correction, we used the corresponding cross section from TENDL-2017. This results, for example at 14 – 15 MeV, in ≈ 10% decrease of the ^{48}Ti(n,n'γ_{984keV}) cross section, see Fig. 2.*

In addition to the "differential" cross section measurements overviewed above, the integral experiments, i.e. in this case the cumulative γ-ray yield measurements in the wide and smooth neutron field, could be useful and independent information. However, we know of only one such benchmark: Yu.G. Kosyak et al. have measured in the year 1993 the discrete γ-rays yields from a natural Ti foil irradiated in the fast neutron field produced by the fission power reactor VVR [33]. Regrettably the observed discrete γ-ray transitions resulting from the ^{48}Ti(n,n'γ) reaction were reported in relative units and thus cannot be used for validation of the cross section. The authors have also measured the angular distributions for several discrete γ-rays, but regrettably not for the 984-keV transition.

2.2 Cross sections measured by detection of discrete inelastically scattered neutrons.

Below the incident neutron energy 2.344 MeV, i.e. the excitation threshold of the second excited state 2.296 MeV of Ti^{48}, the ^{48}Ti(n,n′) reaction is identical to ^{48}Ti(n,n′γ). Hence the discrete neutron inelastic scattering data measured below 2.3 MeV may be straightforwardly used for evaluation of the 984-keV γ-ray production cross section. An additional advantage of inelastic cross sections is that most often they are measured relative to the H(n,n) cross section which is a standard practically unchanged over many years.

M.B. Pasechnik et al. have measured in 1969 the partial cross section for excitation of the 0.984 MeV state through the Ti(n,n') reaction [34]. The data were obtained by the time of flight technique with a fast scintillator positioned at many scattering angles from 30^o to 135^o, relative to n-p scattering and were corrected for finite size of the metallic sample. *The neutron energy selected in that experiment, 2.9 MeV, is above the threshold of ^{48}Ti(n,n$_2$) and thus is not suitable for evaluation of ^{48}Ti(n,γ_{984keV}).*

E. Barnard et al. have published in 1974 the inelastic neutron scattering cross section for natural Ti feeding the 984-keV state in ^{48}Ti [35]. The measurements were done at Argonne National Laboratory from 1.28 to 1.49 MeV with a "broad" neutron energy resolution ≈ 20 keV and at Pelindaba from 1.07 to 1.50 MeV with a "good" resolution (5 – 10) keV. Both experiments have employed the time of flight technique. The angular distribution of inelastically scattered neutrons observed in the experiment with broad resolution was found to be symmetric about 90^o and nearly isotropic. The absolute normalization was determined relative to the differential elastic scattering cross section of carbon. The measured results were corrected for sample finite size effects using a Monte Carlo procedure. *We have divided the data of Bernard by the ^{48}Ti abundancy 0.7372 to convert them to the cross section for ^{48}Ti(n,n$_1$)^{48}Ti.*

E. Almen-Ramström has measured the inelastic cross section for natural Ti in the energy range 2.0 to 3.25 MeV [36]. Regrettably, the resolution of the ToF spectrometer was not sufficient to separate the neutrons feeding two first excited states 0.88 MeV and 0983 MeV in ^{46}Ti and ^{49}Ti. *This fact as well as excitation of nuclear levels in these nuclei above 2.1 MeV prevent the use of Almen's data in the present evaluation.*

I.A. Korzh et al. have reported in 1977 the partial cross sections of the ^{48}Ti(n,n') reaction at 1.5, 2.0, 2.5 and 3.0 MeV, which he derived from measurements with an elemental titanium sample [37]. The angular distribution of inelastically scattered neutrons at angles from 20^o to 150^o was observed to be isotropic. The total uncertainty was reported as ≈ 8%. *In our evaluation we consider the measured data of Korzh* *only at 1.5 and 2.0 MeV where only ^{48}Ti(n,n$_1$) is kinematically allowed. At higher neutron energies 2.5 and 3.0 MeV the excitation of the ^{48}Ti levels U_2 = 2.296 MeV, U_3 = 2.421 MeV, U_4 = 2.465 MeV becomes possible, however the authors have reported only the ^{48}Ti(n,n$_2$) and ^{48}Ti(n,n$_3$) cross sections at 3.0 MeV.*

W.E. Kinney and F.G. Perey have presented in 1973 the measured neutron elastic and inelastic scattering cross sections for natural titanium at 11 energies between 4.07 and 8.56 MeV [38]. The data were obtained with the conventional time-of-flight technique at the ORNL Van de Graaf accelerator. Neutrons were produced in a gas cell via the D(d,n) reaction. The neutrons, scattered by a natural titanium cylindrical sample, were detected by three NE-213 liquid scintillators at angles ranging from 15 to 140 degrees. The partial inelastic scattering to the discrete levels was found from the Legendre fit to the angular differential data. The final error analysis included uncertainties in the geometrical parameters and uncertainties in the finite sample corrections estimated from Monte Carlo simulation results. The absolute normalization and detector efficiency have been derived from the n-p scattering measurements, the common uncertainty associated with them was 7%. *Since the authors reported the inelastic scattering cross sections on natural titanium, we divided their data presented in EXFOR by 0.7372 to get the corresponding data for isotope ^{48}Ti as a target.*

A. Smith et al. have measured in 1978 the angular differential cross sections for the inelastic neutron excitation of 12 discrete states in titanium in the incident-neutron energy range 1.5 to 4.0 MeV [39] using a ten-angle fast neutron time-of-flight system. The neutron source was the ^{7}Li(p,n) reaction. The absolute normalization of the Ti(n,n') cross section was obtained relative to H(n,n). The elastic neutron-scattering cross section of carbon was determined concurrently in order to validate the performance of the measurement system. All experimental results were corrected for beam attenuation, angular resolution and multiple-event effects using a combination of analytical and Monte Carlo procedures. The angle-integrated cross sections were deduced from least-squares fitting by Legendre polynomial series to the measured angular distributions. The estimated uncertainties were less than 3 to 5% due to normalization procedures, 2 to 5% due to corrections and ≈ 10 to 20% due to counting statistics and background. *We also converted the Ti inelastic experimental data of Smith and co-workers to the isotope cross section using the ^{48}Ti abundance 0.7372*.

2.3 Angular distribution of the 984-keV γ-rays.

The angular distribution of the 984-keV γ-rays was measured only by Abbondanno [24] and Connel [28] and only at the 14 MeV incident neutron energy. Their data (cross section as symbols and adjusted fits as black curves) are shown in Fig. 1. It is seen that the two existing measurements do not agree with each other at the overlapping angles. The evaluations ENDF/B-VIII.0 [40] and TENDL-2017 [25] predict an isotropic distribution. For comparison we also plotted the evaluated data of M. Savin et al. for the 847-keV γ-rays from the ^{56}Fe(n,n'γ) reaction [41].

Summarizing existing information, we state that additional measurements and re-evaluation of the angular distribution of the 984-keV γ-rays are needed. In the meantime, obtaining the angular integrated cross section *^{48}Ti(n,n'γ_{984})* from the measurements at angles different from 65^{o} or 125^{o} the correction factor is taken from Abbondanno's angular distribution at 14 MeV.

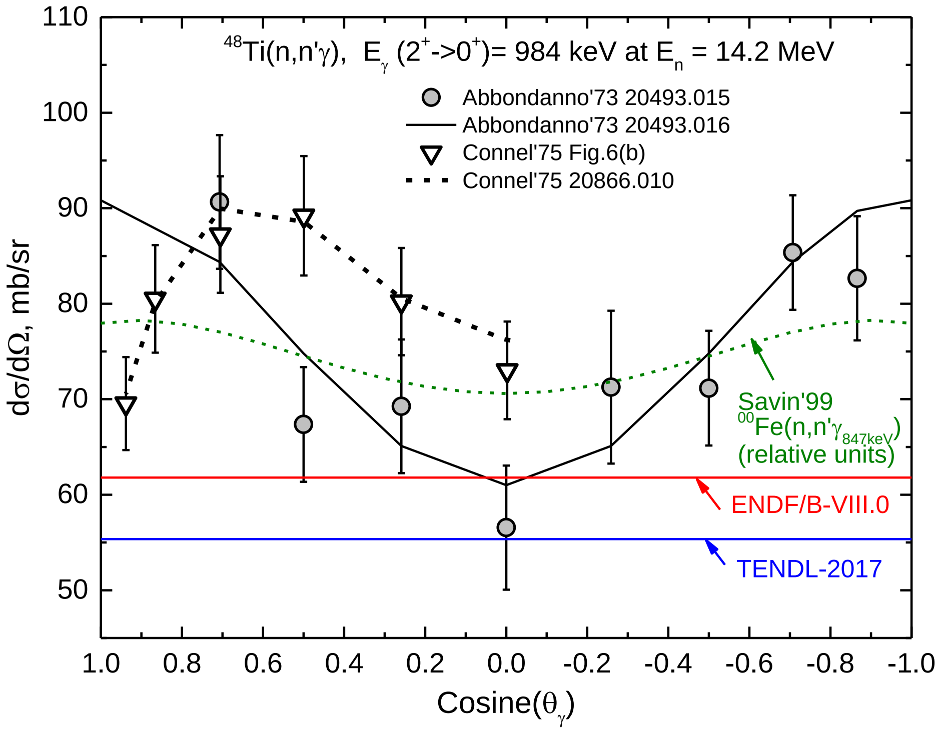

Fig. 1. Angular distribution of 984-keV γ-rays from the ^{48}Ti(n,n') reaction. Symbols - experimental data of Abbondano [24] and Connel [28] (symbols and black curves). Evaluations - ENDF/B-VIII.0 (red curve), TENDL-2017 (blue) and Savin [41] for ^{56}Fe(n,n'$γ_{847keV}$) (green dash).

2.4 Intercomparison of existing experimental cross sections for ^{48}Ti(n,n'γ) and ^{48}Ti(n,n').

The known measurements for the ^{48}Ti(n,n') reaction in the neutron energy range from threshold 1.004 MeV up to 2.344 MeV, the threshold of ^{48}Ti(n,n_2), are plotted in Fig. 2. At such incident energies the γ-ray production is identical to the inelastic neutron scattering. As seen, the existing experimental data show strong energy fluctuations which reflect the low density of the unbound states in compound nucleus ^{49}Ti. The varying width of resonances observed in the different experiments is a result of the different energy resolution which varies from 10 to 50 keV as seen in Table 1. It is also noticeable that positions of resonances are slightly different, this points to systematic uncertainties in the neutron energy calibration procedures.

For the purposes of comparison, the evaluated cross sections from JEFF-3.3 [42] and ENDF/B-VIII.0 [40] are also depicted in Fig. 2. One can notice that contemporary existing evaluations do not reproduce experimentally observed details of the ^{48}Ti(n,n'γ) excitation function above its threshold – a drawback which should be addressed in the next releases of the evaluated data libraries.

Such strong variable energy dependence of the cross section makes it difficult to use the ^{48}Ti(n,n'γ) reaction as a reference below 2 MeV. For these reasons we excluded this energy range and all experimental data there from our present evaluation.

The cross sections above a neutron energy of 2.344 MeV, the threshold of ^{48}Ti(n,n_2), are shown in Fig. 3. The data measured by detection of 984-keV γ-rays are plotted as closed symbols. They agree with each other typically within the uncertainties except those of Engesser, Arya and Lashuk (the latter systematically deviate from the bulk of the others above 6 MeV – *we have disregarded these 5 points in our evaluations).*

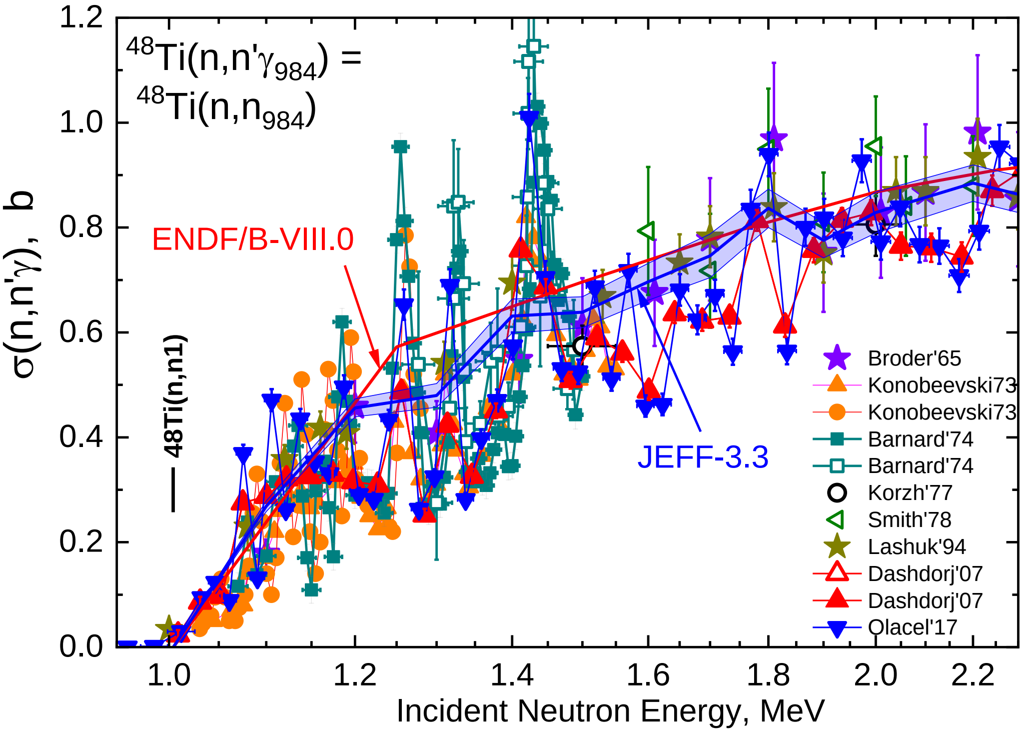

Fig. 2. Cross section of the ^{48}Ti(n,n') reaction from its threshold 1.001 MeV up to the (n,n_2) threshold 2.344 MeV. Symbols - experimental data measured by detection of discrete γ-rays (closed) and neutrons (open). Thick curves - evaluated data from JEFF-3.3 including uncertainty (blue) and ENDF/B-VIII.0 (red).

Two data sets of Olacel et al. are shown in Fig. 3: the original authors' data for ^{48}Ti(n,n'γ_{984}), which include a contribution from ^{49}Ti(n,2nγ_{984}) (since a natural titanium sample was used in the experiment), and those we obtained after subtraction of latter reaction:

$$^{48}\mathrm{Ti}(n,n'\gamma_{984}) = {}^{48+49}\mathrm{Ti}(n,n'\gamma_{984} + 2n\gamma_{984}) - 0.0544/0.7372 * {}^{49}\mathrm{Ti}(n,2n\gamma_{984}) \qquad (1)$$

An additional source of 984-keV γ-rays opens at 9.314 MeV, i.e. threshold of the ^{49}Ti(n,2n_{984}) reaction, and becomes comparable with or exceeds the uncertainties of the experimental data at 14 MeV and higher neutron energies. The ^{49}Ti(n,2nγ_{984}) cross section is from TENDL-2017 [25].

The same procedure was applied to the Nelson et al. data measured with a natural Ti sample. Two data sets correspond to the cross sections obtained relative to Li(n,n'γ) and Fe(n,n'γ) cross sections.

In the considered energy range the partial neutron inelastic scattering exciting the 2nd, 3rd, … levels of ^{48}Ti reach their maxima and then decrease due to competition from other open channels. We tried to determine the 984-keV γ-ray production cross section σ(n,n'γ_{984}) from the sum of *i* partial inelastic cross sections σ(n,n_i) following this equation:

$$\sigma(n,n'\gamma_{984}) = \sigma(n,n_1) + \sum_{i=2}\sigma(n,n_i) * BR \qquad (2)$$

where *BR* is the branching ratio of the 984-keV γ-ray production to the total inelastic scattering, which varies between 1.0 and 0.95 (for more details see [8]).

Such a conversion of the inelastic cross section into the gamma production is possible for the data of Korzh [37], Kinney [38] and Smith [39] since they have measured and reported the partial inelastic scattering to the 2nd and higher excited levels of ^{48}Ti. Fig. 3 shows their originally measured σ(n,n_1) data as open symbols, whereas the σ(n,n'γ_{984}) data derived with the help of Eq. (2) are plotted as the same but closed symbols. As seen, the obtained σ(n,n'γ_{984}) data often but not always agree with direct measured σ(n,n'γ_{984}). The reason could be missed inelastic transitions to the discrete or continuum levels due to the finite threshold of the neutron spectrometers. *To avoid possible systematic underestimation, we disregard the partial (n,n') measurements of Korzh, Kinney, Smith and Almen in the present evaluation.*

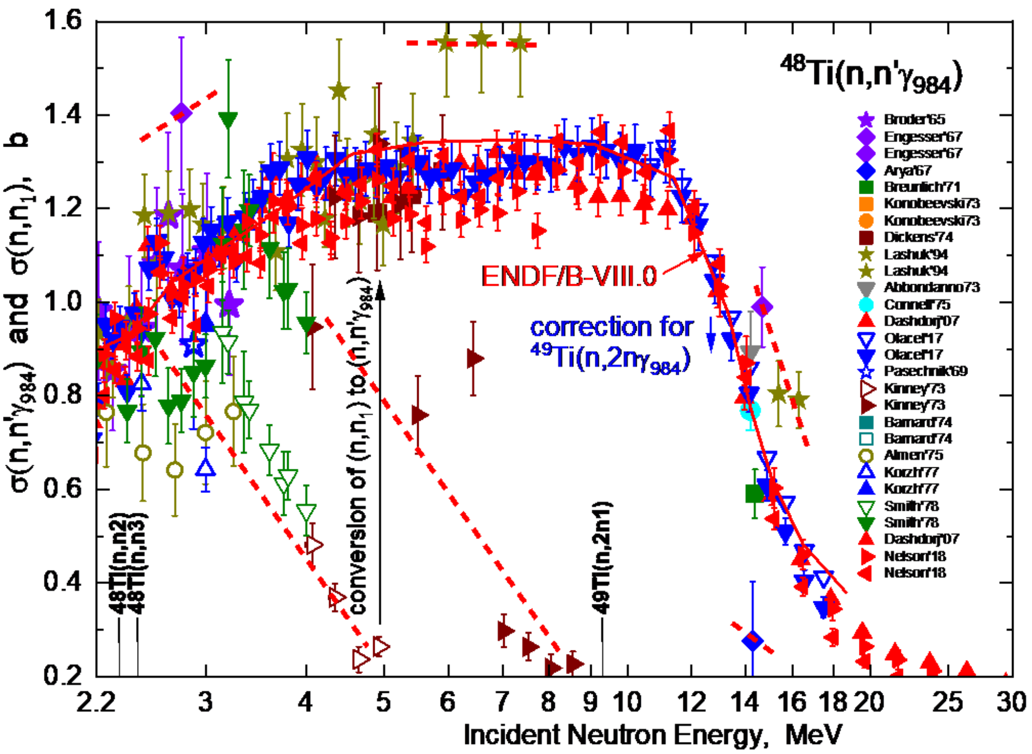

Fig. 3. Cross section of the ^{48}Ti(n,n'γ_{984}) and ^{48}Ti(n,n$_1$) reactions in the energy range from (n,n$_2$) threshold 2.344 MeV to 18 MeV. Symbols - experimental data measured by detection of discrete γ-rays (closed) and neutrons (open). The (n,n'γ_{984}) data computed from the original (n,n$_1$) data are plotted as closed and open symbols. The original Olacel ^{48}Ti(n,n'γ_{984}) data and those after subtraction of ^{49}Ti(n,2nγ_{984}) are shown by open and closed symbols. Dashed red curve indicates the experimental data not agreeing with the bulk of the others and disregarded in the present evaluation. Red curve - evaluated cross section from ENDF/B-VIII.0.

It worthwhile to note that at neutron energies near 14 - 15 MeV, which is important for fusion oriented applications, there were 6 independent measurements of the 984-keV γ-ray yield carried out with use of the 14 MeV neutron generators, but all were before 1975: Lashuk [17], Engesser [18], Arya [21], Breunlich [22], Abbondano [24], Connell [28]. After the year 2007 three new experiments of Dashdorj [31], Olacel [9] and Nelson [11], [12], which employed white neutron sources, provided the ^{48}Ti(n,n'γ_{984}) excitation function in a wide energy range. Comparing all these data we have excluded from the evaluation the oldest and deviating measured results of Lashuk, Engesser and Arya. The remaining data sets agree with each other within reported 1-3 standard uncertainties.

3. The non-model evaluation of the $^{48}Ti(n,n'\gamma_{984keV})$ cross section

The non-model evaluation of the 983.5-keV γ-ray production cross section for neutron inelastic scattering on ^{48}Ti in the energy range from 2 to 16 MeV was performed by the least squares method implemented in the GMA code [6], [7].

Ten experimental data sets included in the GMA fit are listed in Table 2 and plotted in Fig. 4. Eight of them were measured by the direct detection of the 984-keV γ-rays. The results of other experiments (incident neutron energies below 2.3 MeV, discrete neutron inelastic scattering, …) were excluded from evaluation as explained in the previous section.

In the first evaluation run the energy shape of the ENDF/B-VIII.0 $^{48}Ti(n,n'\gamma_{984keV})$ cross section was used as a *prior* for the linear interpolation of the experimental cross section values to the chosen common neutron energy nodes, then it was replaced by the outcome from the GMA run. The energy nodes were set with a step 60 – 200 keV below 4 MeV to reproduce the cross section fluctuations (a typical amplitude is ±10%) confirmed by several experiments. The distance between energy nodes was increased to 0.4 - 0.7 MeV at higher energies, since the cross section was assumed to be smooth there.

Table 2 also lists the neutron energy range and number of energy points (after reduction to the common nodes) from each experiment contributing to the GMA fit. The corresponding relative weights show a dominant contribution of the most recent measurements to the evaluation. The chi-squared parameter χ^2 equals to 1.02. This means that weighted deviations between the measured and evaluated values is close to the experimental uncertainties.

TABLE 2. EXPERIMENTS SELECTED FOR EVALUATION OF THE $^{48}Ti(n,n'\gamma_{984keV})$ CROSS SECTION.

No.	Author, Year.	Type of Cross Section	Used Neutron Energy Range	Number of Points	Relative Weight
1	Broder, 1965	absolute	2.11 – 3.2 MeV	10	0.005
2	Lashuk, 1994	absolute	2.05 - 5.6 MeV	18	0.007
3	Breunlich, 1971	absolute	14.4 MeV	1	0.013
4	Abbondanno, 1973	absolute	14.2 MeV	1	0.012
5	Dickens, 1974	absolute	4.8 – 6.0 MeV	3	0.016
6	Connell, 1975	absolute	14.2 MeV	1	0.018
7	Smith, 1978	absolute	2.05 – 2.18 MeV	2	0.008
8	Dashdorj, 2007	absolute	2.05 – 16.0 MeV	36	0.028
9	Olacel, 2017	absolute	2.05 – 16.0 MeV	38	0.027
10	Nelson, 2018	shape	2.05 – 16.0 MeV	36	
	Total		***2.05 – 16.0 MeV***	***172***	

The results of the GMA fit, i.e. the cross sections and uncertainty, are depicted in Fig. 4 in the energy range 2 to 16 MeV. Since the fluctuations are well visible below 3 MeV, we increased the low energy limit up to 2.8 MeV above which the evaluated $^{48}Ti(n,n'\gamma_{984keV})$ cross section could be recommended as a reference. The numerical data are listed in Table 3.

Fig. 5 displays the energy-energy correlation matrix, which shows rather strong correlations ≈ 0.5 between neutron energies differing up to 90%. This reflects the dominance of systematic uncertainties (absolute normalization, γ-ray detector efficiency etc.) over statistics especially for those experiments which provide the cross section in the whole energy range of interest.

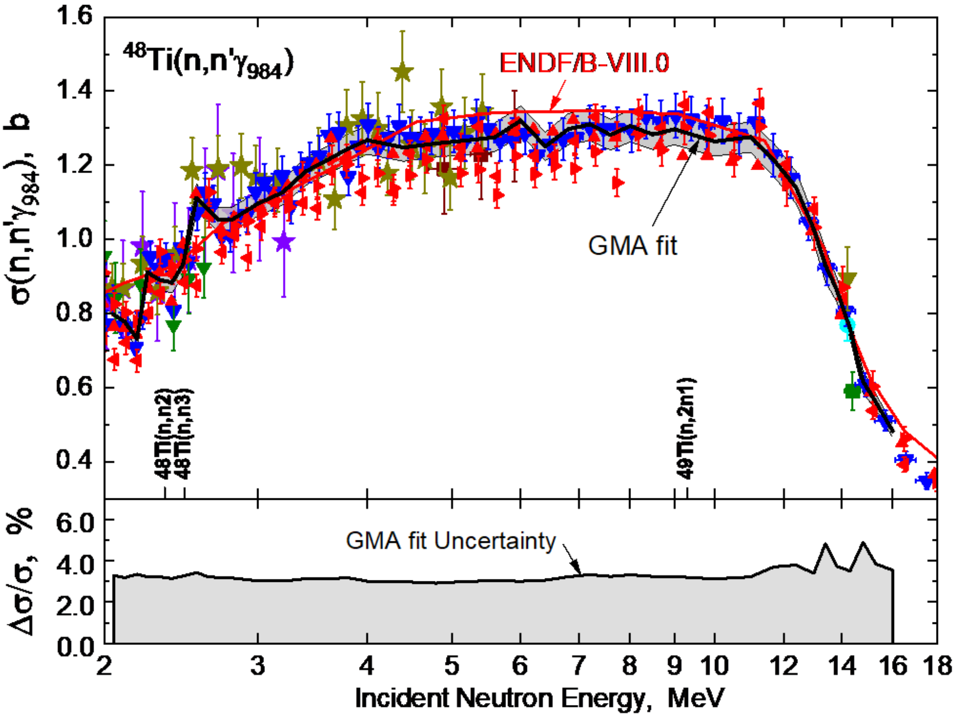

Fig. 4. Cross section (top) and uncertainty (bottom) of the $^{48}Ti(n,n'\gamma_{984})$ reaction in the energy range 2 to 16 MeV. Closed symbols - experimental data measured by detection of 984-keV γ-rays and selected for the present evaluation. Curves - GMA fit (black) and ENDF/B-VIII.0 (red).

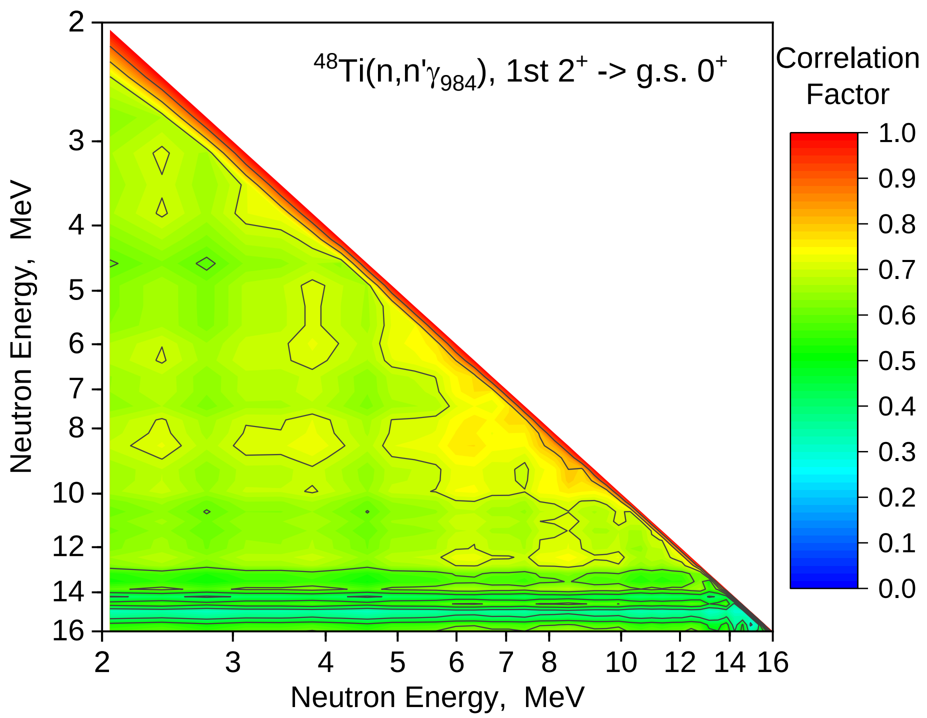

Fig. 5. Energy–energy correlation matrix for the $^{48}Ti(n,n'\gamma_{984})$ reaction cross section resulting from the GMA fit.

TABLE 3. RECOMMENDED GMA EVALUATED CROSS SECTION AND UNCERTAINTY FOR THE ^{48}Ti(N,N'γ_{984}) REACTION IN THE ENERGY RANGE 2.8 TO 16.0 MEV.

E, MeV	σ(E), b	Δσ(E)/σ(E), %	E, MeV	σ(E), b	Δσ(E)/σ(E), %
2.80	1.053	3.16	7.60	1.282	3.24
3.00	1.096	3.03	8.00	1.306	3.32
3.20	1.126	3.01	8.50	1.283	3.24
3.40	1.183	3.13	9.00	1.297	3.23
3.60	1.213	3.12	10.00	1.264	3.12
3.80	1.244	3.18	11.00	1.276	3.22
4.00	1.268	3.01	11.70	1.214	3.70
4.40	1.248	2.99	12.40	1.140	3.78
4.80	1.259	2.92	13.00	1.027	3.39
5.20	1.267	3.01	13.40	0.930	4.82
5.60	1.275	3.04	13.80	0.865	3.74
6.00	1.321	3.01	14.30	0.759	3.49
6.40	1.251	3.06	14.80	0.616	4.89
6.80	1.298	3.23	15.30	0.562	3.84
7.20	1.310	3.33	16.00	0.483	3.54

One of the authors of the present work has evaluated in 1998 the 984-keV production cross section (0.666 ± 0.061) b for the Ti(n,n'+2n) reaction at 14.5-MeV incident energy [43]. Extracting from this value the cross section 0.807 b for reaction ^{49}Ti(n,2n) and converting then to ^{48}Ti(n,n'γ_{984keV}) we get (0.844 ± 0.083) b. This value agrees within almost one standard deviation with (0.702 ± 0.030) b obtained in the present evaluation. The difference could be attributed to the impact of the Dashdorj and Olacel precise measurements that appeared after 1998.

4. The ^{48}Ti(n,n'γ_{984keV}) and other reference cross sections

After the evaluation of the ^{48}Ti(n,n'γ_{984}) cross section we can combine it with other discrete γ-ray production reactions, namely the standard ^{10}B(n,$\alpha_1\gamma$) [1] and the reference ^{7}Li(n,n'γ) [5], to establish the energy range which can be covered by the combination. Corresponding evaluated cross sections and uncertainties in the corresponding energy intervals are displayed in Fig. 6. It is seen that the overlapping of energies allows covering of the wide energy interval from thermal to 16 MeV. Since two reactions, ^{10}B(n,$\alpha_1\gamma$) and ^{7}Li(n,n'γ), produce a γ-ray of the same energy 478 keV, their simultaneous use in one TOF experiment could be an additional advantage.

The uncertainties of these evaluated cross sections, shown in the bottom of Fig 6, equal to (1 – 2)% for the standard reaction ^{10}B(n,$\alpha_1\gamma$), ≈ 2% for the reference ^{7}Li(n,n'γ) and (3 – 5)% for ^{48}Ti(n,n'γ_{984}). The notably higher uncertainty for the latter arises from the lower number and more discrepant measurements involved in evaluation of ^{48}Ti(n,n'γ_{984}) in comparison with ^{7}Li(n,n'γ).

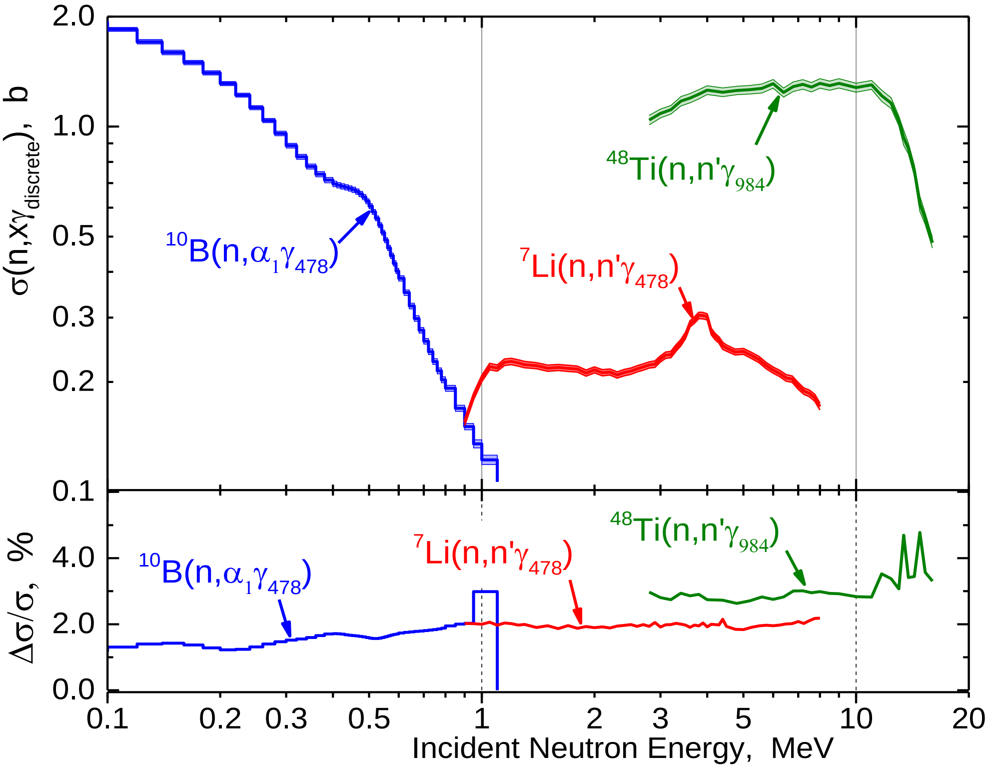

Fig. 6. Evaluated discrete γ-ray production cross sections for the $^{10}B(n,\alpha_1\gamma)$, $^{7}Li(n,n'\gamma)$ and $^{48}Ti(n,n'\gamma)$ reactions in the neutron energy ranges where they are recommended for use as a standard or reference (top) and their uncertainties (bottom).

5. Conclusions

Experimental data relevant for evaluation of the ^{48}Ti(n,n′γ_{984}) cross section were collected and critically reviewed. Up to now there are known thirteen independent measurements of the 984-keV gamma yield and six measurements of the partial inelastic neutron scattering cross sections populating the first and other levels of ^{48}Ti. Some of these have been carried out 40 - 50 years ago and have used large samples, detectors with low energy resolution, energy fluctuating reference reactions etc. Only two experiments have used samples made of enriched ^{48}Ti. Only three recent independent experiments have delivered an excitation function for this reaction in the whole energy range of interest - from threshold up to 20 MeV.

Considering the present status of the experimental data we will still recommend the new and precise measurements of ^{48}Ti(n,n′γ_{984}) cross section, especially above 6 MeV and at 14 MeV. This is also true for the angular distribution of the 984-keV γ-rays, since up to now only two and contradicting measurements at 14 MeV are known. At this time the modern evaluated cross section libraries contain isotropic distributions of the secondary gammas.

Practically all measurements at 14 MeV and nearby need a correction to exclude the contribution from the ^{49}Ti(n,2nγ_{984}) reaction. Since there are no measurements so far for this reaction, we have to rely on the evaluated cross section, e.g. from TENDL-2017. Thus, the measurements of the ^{49}Ti(n,2nγ_{984}) reaction cross section are highly valuable for validation purposes.

In conclusion, 10 experimental data sets from a total of 19 were selected, renormalized to modern references or corrected for the contribution from ^{49}Ti(n,2nγ_{984}) when it was necessary and possible. The final evaluation of the ^{48}Ti(n,n′γ_{984}) cross section was performed by means of the least squares code GMA from 2 to 16 MeV with resultant uncertainty (3 - 5)%.

We recommend using this reaction as a prompt discrete γ-ray reference above 2.8 MeV to avoid the energy fluctuations caused by the unresolved resonances.

The use of the ^{48}Ti(n,n′γ_{984}) reaction in combination with the standard ^{10}B(n,$\alpha_1\gamma$) and reference ^{7}Li(n,n'γ) provides continuous prompt discrete γ-ray reference from thermal to fusion energies.

The comparison of the experimental cross sections with evaluations for the ^{48}Ti(n,n'γ) reaction has shown that contemporary libraries do not reproduce sufficiently well (JEFF-3.3) or at all (ENDF/B-VIII.0) the resonance type structure observed between reaction threshold and 2.8 MeV – a drawback which should be addressed in the next releases.

Acknowledgment

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