https://doi.org/10.61092/iaea.nhh2-15va
INDC(NDS)- 0739
Distr. ST, G

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S.P. Simakov
Karlsruhe Institute of Technology, Eggenstein-Leopoldshafen, Germany

R. Capote
Nuclear Data Section, International Atomic Energy Agency, Vienna, Austria

R.O. Nelson
Los Alamos National Laboratory, Los Alamos, NM, USA

V.G. Pronyaev
Atomstandart, State Corporation Rosatom, Moscow, Russia

June 2018

IAEA Nuclear Data Section
Vienna International Centre, P.O. Box 100, 1400 Vienna, Austria

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Printed by the IAEA in Austria

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ABSTRACT

The yield of the 478 keV γ-rays from the ^{7}Li(n,n′γ) reaction has been evaluated in the neutron energy range from threshold 0.6 MeV up to 17 MeV. For this purpose, all currently available measured discrete gamma production and partial neutron inelastic cross sections were collected and thoroughly analysed, the suitable ones were selected for the evaluation process. The non-model evaluation of the ^{7}Li(n,n′γ) cross section and its covariance matrix was performed by means of the least squares method implemented in the GMA code. This evaluation is recommended for inclusion in the standards in the energy range from 0.9 to 8 MeV where the ^{7}Li(n,n′γ) cross section has maximal values, the evaluation is smooth and has uncertainty ≈ 2%.

June 2018

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1. Introduction

The neutron reaction cross section standards [1] are the most precisely known quantities, which are used in many applications as reference values. Additionally, there are evaluated cross sections which have a status of reference (recommended) cross sections which did not reach the accuracy of standards yet but meantime could be used in the different applications. Despite numerous measurements and recognition of importance for proper applications, no prompt γ-ray production cross section has been established as a reference so far.

The team developing standards has considered the different aspects of practical use of the candidate reactions and recommended for evaluation following reactions: ^{7}Li(n,n′γ_{478keV}) in the energy range from 0.8 to 10 MeV and ^{48}Ti(n,n′γ_{984keV}) – from 3 to 16 MeV [2]. These two reactions as addition to the existing ^{10}B(n,$\alpha_1\gamma_{478keV}$) standard evaluation in the energy range from 10^{-5} eV to 1 MeV will cover together the energy range between 10^{-5} eV and 15 MeV relevant to fission and fusion applications.

The present document collects all currently available measured discrete γ-ray production and neutron inelastic cross sections on isotope ^{7}Li and elemental Li, selects appropriate ones and provides the non-model evaluation of the ^{7}Li(n,n′γ_{487keV}) cross section.

The evaluation of the other candidate reaction ^{48}Ti(n,n′γ_{984keV}) is reported in [3].

2. Experimental data

The threshold for the inelastic neutron scattering on ^{7}Li is 546.277 keV when population of the first excited state at 477.761 keV in the target nucleus becomes kinematically allowed. Since this first state is a single bound level of ^{7}Li (the unbound ones decay with emission only of tritons and α-particles), the cross sections for the 478 keV γ-ray production and inelastic scattering are equal. Additionally, since the spin of the ^{7}Li first excited state is $1/2^{-}$, the angular distribution of the (n,n'$\gamma_{478\ keV}$) photons is isotropic. Therefore, a measurement at any emission angle determines the total gamma production cross section by multiplying the differential cross section with 4π.

The known measurements of the cross sections for the 478 keV γ-ray production and neutron inelastic scattering feeding the first excited level in ^{7}Li are summarised in Table 1 and plotted in Fig. 1.

In total, 14 independent measurements of the 478 keV γ-ray yield and 5 measurements of inelastic neutron scattering have been reported since 1955. Approximately half of known experiments have used enriched ^{7}Li samples thus providing the isotopic cross section. If the measurement was done with natural lithium, the authors usually made a proper correction for the 92.41% abundance of ^{7}Li, otherwise we did the conversion ourselves.

The numerical data obtained in experiments were taken, as a rule, from the EXFOR database [4]. In a few cases the data and more detailed information about experiments were found in the original publications or through the private communication with authors.

The next two subsections summarise the most important details of all experiments which eventually impact on inclusion of the data sets in the present evaluation and on the handling of their uncertainties *(our negative decision or modifications applied to these data are highlighted by italic font).*

TABLE 1. KNOWN MEASUREMENTS OF THE CROSS SECTIONS FOR THE ^{7}Li(n,n′γ_{478keV}) AND ^{7}Li(n,n$_1$) REACTIONS.

Author Reference	Year Lab	Neutron Energies and Resolution	Sample	Detector, Energy Resolution, Angle	Absolute normalization of σ	Corrections applied	EXFOR entry
Registration of the 478 keV γ-rays from the ^{7}Li(n,n′γ) reaction							
J.M. Freeman et al. [5]	1955 Harwell	0.5 - 1.6 MeV ΔE = 20 keV	^{nat}Li	Stilbene and NaI ≈ 90°	n-flux measured by BF_3	applied for n and γ	21077.002
N.A. Bostrom et al. [6]	1959 Texas Nuc.	1.01 MeV ΔE = 10 keV	^{nat}Li	NaI(Tl) ≈ 67°	n-flux measured by calibrated BF_3	applied only for γ	11130.004
J. Benveniste et al. [7]	1962 Livermore	13.6 - 14.3 MeV	LiH	NaI ≈ 30°- 150°	n-flux measured by α associated	applied for n and γ	11165.002
M.E. Battat et al. [9]	1962 LANL	14 MeV	-	-	-	-	11023.002
G.T. Western et al. [10]	1965 G. Dynam.	14.6 MeV ΔE = 200 keV	^{7}Li	NaI(Tl) at 90°	n-flux measured by plastic scintil.	applied for n and γ	12681.005
J.C. Hopkins et al. [11], [12]	1968 LANL	5.74, 7.5 MeV ΔE = 230, 170 keV	^{7}Li	anti-coinc. NaI, TOF, 45° - 150°	relative to ^{1}H(n,p)	applied for n	11153.024
G. Presser et al. [13]	1972 Frankfurt	1.0 – 5.0 MeV (50 keV) 4.8 – 8.8 MeV (50 keV) 5.0 – 5.3 MeV (50 keV) 19 – 21 MeV (100 keV)	^{nat}Li	Ge(Li), ΔE =4.0 keV	n-flux measured by plastic scintillator	n - scattering was neglected; γ - applied	20534.002 20534.003 20534.004 20534.005
J.K. Dickens et al. [14], [15]	1974 ORNL	0.55 – 20.6 MeV ΔE = 0.15 - 0.20 MeV	^{nat}Li	ToF, NaI at 125°	n-flux measured by plastic scintill.	applied for n and γ	10502.003
D.L. Smith [16]	1976 ANL	0.6 - 4.0 MeV ΔE = 100 - 60 keV	^{7}Li	GeLi, ΔE = keV, ~ 90°	relative to ^{235}U(n,f)o	applied for n and γ	10641.002
G.L. Morgan [17]	1978 ORNL	0.5 – 19.8 MeV ΔE = 7 - 210 keV	^{7}Li	NE-213, 126°	n-flux measured by NE-213 scintill.	applied for n and γ	10788.006
V.M. Bezotosnyy et al. [18]	1978 KIAE	14.0 MeV, ΔE = 17 keV	^{nat}Li	NaI(Tl), ΔE = 4.0 keV	n-flux measured by associated α	applied for n and γ	40516.003
D.K. Olsen et al. [19]	1980 ORNL	0.5 – 5.5 MeV ΔE = 60 - 500 keV	^{7}Li	GeLi, 126°	relative to ^{1}H(n,p)	applied for n and γ	10787.002

Author Reference	Year Lab	Neutron Energies and Resolution	Sample	Detector, Energy Resolution, Angle	Absolute normalization of σ	Corrections applied	EXFOR entry
M. Nyman et al. [20]	2016 IRMM	0.6 – 1.8 MeV, L=100m 0.6 – 1.6 MeV, L=199m ΔE = 1.4 keV - 44 keV	^{nat}Li	ToF, 12 HPGe array at 110^o, 125^o, 150^o	relative to ^{235}U(n,f)	applied for n and γ	23288.002 23288.003
R. Nelson et al. [21], [22]	2018 LASL	0.8 - 27 MeV, ΔE = 50 - 100 keV	^{nat}LiF	ToF, 20 HPGe array, 27^o- 142^o	rel. to ^{56}Fe(n,n'γ) and ^{235}U(n,f)	applied for n and γ	private commun.
Registration of inelastically scattered neutrons from the (n,n_1) reaction feeding the 478 keV excited state of ^{7}Li.							
R. Batchelor et al. [23]	1963 AWE	1.5, 3.35, 4.0 MeV ΔE ≈ 80 - 60 keV	^{nat}Li	TOF, Scintilator 30^o - 115^o	relative to ^{1}H(n,p)	applied for n	21147.047
N.P. Glazkov et al. [24], [25]	1963 IPPE	1.0, 1.2 MeV ΔE = 100 - 150 keV	^{nat}Li	^{3}He spectrometer all angles	relative to ^{56}Fe(n,n')	applied for n	40680.003
J.C. Hopkins et al. [11], [12]	1968 LANL	3.35, 4.83 MeV ΔE = 62, 47 keV	^{7}Li	TOF, NE102A 45^o - 150^o	relative to ^{1}H(n,p)	applied for n	11153.017
H.H. Knitter et al. [26], [27]	1968 Geel	1.1 – 2.3 MeV ΔE = 100 - 79 keV	^{7}Li	TOF, Scintillator 22^o - 152^o	relative to ^{1}H(n,p)	applied for n	20395.004
H. Knox et al. [28]	1978 Ohio	2.3 – 4.1 MeV ΔE = keV	^{7}Li	TOF, Scintillator 20^o - 160^o	Relative to ^{1}H(n,p)	applied for n	10914.006

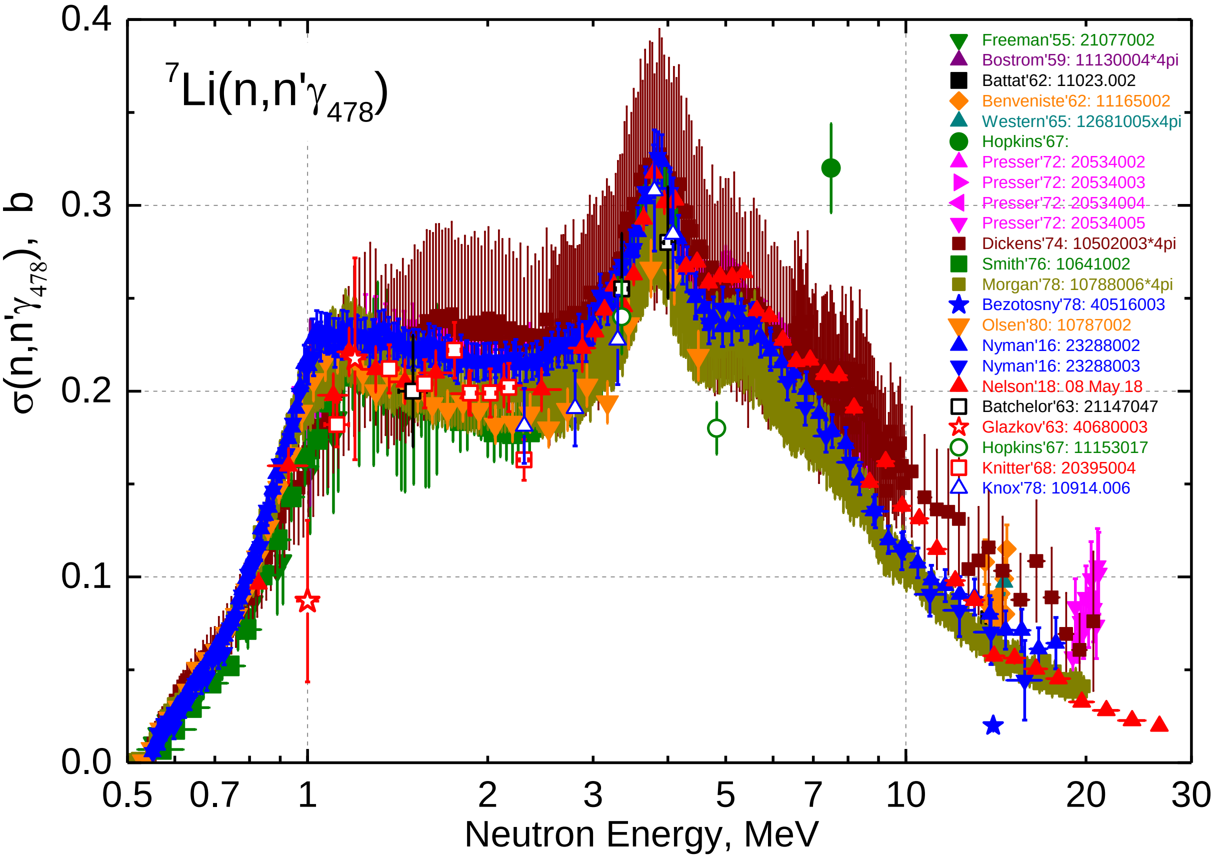

FIG. 1. Available experimental data for the $^7Li(n,n'\gamma_{478keV})$ (closed symbols) and $^7Li(n,n_{478keV})$ (open symbols) reaction cross sections. Uncertainty bars depict the total errors reported by authors. EXFOR entries are shown when available.

2.1 Cross sections measured by registration of the 478 keV γ-rays from the Li(n,n′γ) reaction

The first such measurements have been carried in 1955 by J. Freeman and co-workers who used the Van de Graaf accelerator and a solid ZrT target to produce neutrons with variable energy between 0.54 and 1.65 MeV [5]. The natural Li sample was a hollow cylinder of rather large wall thickness 4.2 cm. The incident neutron flux was measured by absolutely calibrated BF_3 counter. The NaI and stilbene crystal detectors were used to detect the 478 keV gammas from reaction. The statistical uncertainty was between 5% and 30%, the systematic uncertainty ≈ 20%. *Because of the bulk sample and large uncertainties which lead to the small impact of this experiment on the evaluation, we excluded Freeman'55 data from our evaluation.*

In 1959, N. Bostrom et al. have measured the cross section at only one incident neutron energy 1.01 MeV [6]. The experimental arrangement have used the natural lithium ring sample (outer diameter Ø 8.67 cm, inner Ø 5.08 cm, thickness 1.26 cm) placed around the NaI detector. The correction for the neutron multiple scattering in such a rather thick sample was, however, not applied by the authors. The reported cross section uncertainty of 25% is relatively large. *Due to these factors, Bostrom's experiment was excluded from the present evaluation.*

In 1962, J. Benveniste et al. have reported the cross section values in the neutron energy range 13.6 - 14.8 MeV measured with a D-T neutron source and NaI spectrometer [7]. The LiH sample was rather thick. However, the correction for the multiple scattering was handled by the Monte Carlo simulations. The incident neutron flux was determined by counting the associated α-particles. *We interpreted the 11%-12% uncertainty given in EXFOR as a total error. Another paper of the authors [8] has reported following components of systematic uncertainty: neutron source intensity - 2%, multiple scattering ≤ 5%, γ-detector efficiency ≤ 5%. We used this information to calculate the statistical uncertainty from the total error*.

M. Battat reported the cross section (75 ± 15) mb at 14 MeV [9]. This value was reported in the paper of J. Benveniste et al. [7] as a private communication. *Since we did not find original information about this experiment, Battat' data were disregarded in the present evaluation.*

In 1965, G. Western et al. [10] have published the cross sections measured at 14.6 MeV. The sole publication, the General Dynamics laboratory Report WL-TR-64(1965)140, and the EXFOR entry contains sufficient details about this experiment. The authors have used enriched ^{7}Li sample and detected the 478 keV γ-rays by the NaI spectrometer. The incident neutron flux was determined by the NE102 plastic and BF_3 detectors. All necessary corrections were applied. The reported errors include: accumulated count statistics ≤ 5%, absolute normalization uncertainty ≈ 5%, total ≈7%.

In 1968, J. Hopkins et al. have measured the 478 keV γ-ray yield from ^{7}Li at an incident energy of 5.74 and 7.5 MeV [11],[12]. Neutrons were produced by the D(d,n)He3 reaction employing a gas target with a thick entrance window of a Mo. A NaI(Tl) spectrometer surrounded by a large NaI(Tl) anticoincidence shield and the time of flight technique was used for detection of desirable γ-rays and suppression of background. *As can be seen in Fig. 1, the cross section obtained at 7.5 MeV is outside the bulk of known measurements. Due to this reason, data of Hopkins at both energies were disregarded in the present evaluation.*

In 1972, G. Presser et al. [13] have obtained the cross section for the ^{7}Li(n,n'γ) reaction using a metallic natural lithium scatterer and Ge(Li) γ-detector. The monoenergetic neutrons in the three energy intervals 1.0 – 5.0 MeV, 4.4 - 9.0 MeV and 19 - 21 MeV were produced by the T(p,n), D(d,n) and T(d,n) reactions, correspondingly. The incident neutron flux was measured by the thin plastic detector applying a standard technique for calculation of neutron fluxes from the measured recoil proton spectra. No corrections for neutron multiple scattering and neutron-flux attenuation in the lithium ring were applied since authors assumed that these two effects nearly compensate. The uncertainty components given by the authors include the absolute normalization ±15% and energy dependant errors ≥ 3% which we interpreted as statistics.

J. Dickens has reported the first ^{7}Li(n,n'γ) cross section measurement at the ORNL Electron Linear accelerator in 1974 [14], [15]. The photo-nuclear reactions in the Ta target generated neutrons with energies extending up to 20 MeV. The time of flight technique for incident neutrons and their coincidence with the γ-rays pulses from the heavy shielded NaI detector were used to define the incident neutron energies and to select the 478 keV gammas. The contribution of multiple-scattering in the sample was estimated by a Monte Carlo routine and series of approximations. The statistical uncertainty associated with the raw data was below 5% for neutron energies up to 10 MeV, then increasing to 20% at 14 MeV. The absolute normalization of the cross section was obtained from the incident flux measurement by the thin scintillator detector. The uncertainties associated with this procedure yielded an overall absolute error of ±20%. *We have multiplied the original data of author by 4π to get angular integrated cross section*.

In 1976, D. Smith has measured the cross section for the ^{7}Li(n,n`γ) reaction relative to ^{235}U(n,f) in the energy range 0.57 to 4.0 MeV [16]. A pulsed beam of monoenergetic neutrons was produced by the T(p,n) reaction, the scattering sample was fabricated from enriched ^{7}Li, γ-rays were registered by the shielded GeLi detector. Time-of-flight technique was employed to reduce the background. All necessary corrections were applied, the major sources of errors were specified and they did not exceed 5%.

In 1978, G. Morgan [17] has measured the differential cross sections for the production of the 478 keV γ-rays from neutron interactions in ^{7}Li for incident neutron energies between 1 and 20 MeV at the same ORNL Linac facility as used by J. Dickens [14], [15]. In this new experiment, enriched ^{7}Li scatterer and the NE-213 scintillation counter for gammas were used. The author measured the data at the two angles 50^{o} and 126^{o}. However, he has rejected the 50^{o} measurement set of data as being inaccurate due to the numerous problems. The data at 126^{o} were believed to be accurate within the quoted uncertainties. The cross sections were corrected for finite sample effects including neutron transmission, gamma absorption, and neutron multiple scattering using the Monte Carlo code. Two types of data errors are given by the author: statistical uncertainty which varies 1% to 5% for neutron energies interval 0.56 – 15 MeV and overall flux normalization ±10%. *Since 1% uncertainty looks unreliably small we added in our evaluation an additional uncertainty of 5%, also supposing a middle energy range correlation for it.*

V. Bezotosnyy et al. have reported the value of cross section (20 ± 3) mb at 14 MeV in 1978 [18], which is essentially lower than the average value 100 mb observed by many other authors at this energy. *Due to this reason, the experimental point of Bezotosnyy was not included in our evaluation.*

In 1980 D. Olsen and colleagues have performed the third measurement at the Oak Ridge Electron Linear Accelerator employing an enriched ^{7}Li sample and a Ge(Li) detector, positioned at a 22 m flight path [19]. The new cross section data were obtained from threshold up to 5 MeV. A proton recoil detector was used for the incident flux measurement relative to the (n.p) reaction which resulted in the systematic uncertainty of $\approx$ 5%. Additional 3% for absolute normalization comes from the uncertainty of the Ge(Li) detector efficiency measurement. The resultant inelastic scattering cross section was corrected for neutron multiple scattering, neutron flux and γ-ray attenuation and other set-up effects by the Monte Carlo procedures inducing additional overall uncertainty of 3%. Each data point has a statistical uncertainty of 5-7%.

In 2016, M. Nyman and co-workers have published results of precise measurements carried out at the GELINA pulsed white neutron source [20]. The cross sections were measured at the two flight paths 100 and 199 m using 12 large-volume high-purity Ge detectors. The cross sections were obtained relative to ^{235}U(n,f), however the ratio data are not available. From the information published [20] and private communication with the authors, detailed information about uncertainties and cross-correlation between measurements at two different flight paths were received and used in the present evaluation. The main components and correlation matrices reconstructed from these components for both flight paths are illustrated in Fig. 2.

R.O. Nelson and co-workers have measured the Li(n,n_1'γ) cross section at the Los Alamos Neutron Science Center (LANSCE) spallation neutron source facility of the Los Alamos National Laboratory [21], [22]. The sample was a natural LiF optical window. In addition, high-purity metal foils of Fe and Ti were used to perform relative cross section measurements. The GEANIE array of HPGe detectors was used to detect γ-rays. The gamma rays from the first excited states of ^{7}Li, ^{48}Ti, and ^{56}Fe were measured in the same experiment. In another experiment a fission chamber with a ^{235}U foil was used to measure the neutron flux.

The Li(n,n_1'γ) cross section was determined for E > 3 MeV from a relative measurement to ^{nat}Fe(n,n_1'γ) using the Fe(n,n_1'γ) cross sections measured at LANSCE, the recently revised data 0.882*EXFOR 14118002 and EXFOR 13884002. Below 3 MeV the rapidly varying resonance structure in the Fe cross section and different neutron energy resolutions produced fluctuations in the Li(n,n_1'γ) cross sections, and thus was not used in this energy range. The EXFOR 13884002 cross section was normalized to the more accurately determined EXFOR 14118002 Fe cross section measurement. The two Fe measurements made with different samples, detectors and flight paths were averaged to reduce statistical and systematic uncertainties. Being a relative measurement, the cross section depends only on the measurement of the sample areal densities and the relative efficiencies for the different γ-ray energies, and on the accuracy of the separately measured Fe cross section. From 1 to 3 MeV incident neutron energy, the Li(n, n_1'γ) cross section determined using the fission chamber measured neutron flux was used. These data were normalized to the data acquired relative to the Fe(n,n_1'γ) cross section.

The Nelson' data were corrected for angular distribution effects, photon attenuation in the samples, 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%, the statistical errors are less than 2% between 3 and 10 MeV. Below 3 MeV the statistical errors from both the flux measurement and the data are larger.

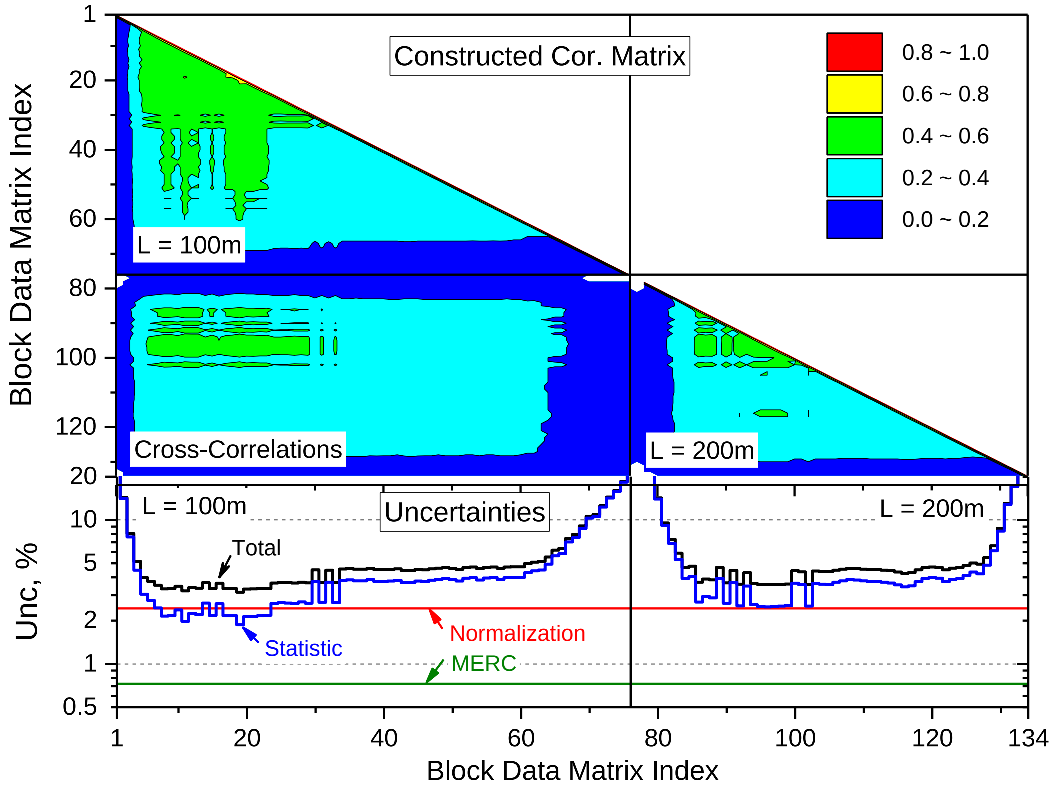

FIG. 2. JRC Geel measurements of ^{7}Li(n,n'$\gamma_{478\ keV}$): correlation matrices and uncertainties for flight paths L = 100 and 200 m including the cross-correlation between them.

2.2. Cross sections measured by registration of neutrons from the ^{7}Li(n,n_1) reaction

In 1963, R. Batchelor and co-workers have measured the cross section of the ^{7}Li(n,n′) reaction by detection of the secondary neutrons [23]. They used a Van de Graaf machine, gaseous tritium and deuterium targets to produce monoenergetic neutrons. The angular distribution of neutrons scattered by natural Li sample was measured by means of the time of flight method employing a scintillation detector. At three incident energies, 1.5, 3.35 and 4.0 MeV, the neutrons feeding the first level of ^{7}Li were separated from elastic and other neutrons. After applying all necessary corrections, the authors reported cross section values with a total uncertainty of 11-15%, which we consider as energy dependant systematic errors.

In 1963, N. Glazkov [24], [25] used the ^{3}He spherical proportional chamber to measure inelastic neutron scattering in the inverse spherical geometry, i.e. when the ^{3}He-spectrometer was located inside the 3 cm thick spherical scatterer. *However, the values reported by the author show a very large uncertainty of 50-25%. Due to this reason we excluded them from the present evaluation.*

In 1968, J. Hopkins et al. have measured the angular differential inelastic neutron scattering cross sections of ^{7}Li at energies of 3.35 and 4.83 MeV [11], [12]. The scattered neutrons were observed by a time of flight spectrometer and were compared with neutron scattering on hydrogen. *As can be seen in Fig. 1, the point at 4.83 disagrees with other known measurements. Therefore, the Hopkins' (n,n') data was not included in the present evaluation, similar as his (n,n'γ).*

H. Knitter et al. have measured in 1968 the angular distribution of neutrons inelastically scattered by ^{7}Li at eight incoming energies between 1.12 and 2.30 MeV by a fast neutron time of flight spectrometer [26], [27]. The length of flight path was chosen sufficiently large to resolve the inelastically scattered neutrons from elastically scattered ones. Neutrons were produced by solid TiT target, the sample was made of the metallic enriched ^{7}Li. Data were corrected for the sample finite sizes and set-up geometry. Absolute cross section was derived from comparison with the H(n,n) differential scattering cross section. The uncertainty components presented in laboratory report [26] include: statistics ≈3%, errors for normalization and elastic peak separation 5%, total uncertainty ≈ 7.5%.

H. Knox et al. have measured in 1978 the differential cross section for the ^{7}Li(n,n$_{478\ \mathrm{keV}}$) reaction [28]. They used the T(p,n) reaction as a neutron source, highly enriched sample and time of flight method. Authors have obtained the integral cross sections from measurements at nine angles between 20^{o} and 160^{o}. The energy dependent uncertainties of cross section reported in EXFOR are only 4 - 5%. *Because of few information about this experiment, which was reported only in the Bulletin of the American Physical Society, we added 10% uncertainty to Knox' data during our evaluation.*

3. GMA evaluation and results

The evaluation of the 478 keV γ-ray production cross section for the ^{7}Li(n,n'γ) reaction is based on the experimental data measured by direct registration of both gammas and neutrons following the inelastic scattering, as discussed in the previous section.

The non-model evaluation of the 478 keV γ-ray production cross section was performed by the least-squares method implemented in the Gauss-Markov-Aitken code GMA [29], [30].

The experiments finally selected for the evaluation are listed in Table 2. Most of them provided an absolute cross section. The data of Smith [16] were taken in the GMA fit as absolute ratio to standard cross section ^{235}U(n,f) known with an uncertainty of 0.5 - 1.5% in the energy range of interest [1] (the latter one was included in the fit as a *pseudo* measurement).

Table 2 also lists the energy range and number of points taken by GMA from the individual experimental data sets. The last column shows the maximum weight of individual point in each data set, which is inversely proportional to the total relative uncertainty. It is seen, the most important contributions to the evaluation are made by the measurements of Nyman, Nelson, Knitter and Smith. The total number of individual experimental points included in the evaluation equals 452.

The ENDF/B-VIII.0 evaluated cross section (designated in the ENDF-6 format nomenclature as MT = 51) for the ^{7}Li(n,n$_{1}$) reaction between 0.5 and 20 MeV [31] was used as *a priori*, since it reasonably and smoothly reproduces the energy dependence of the reaction excitation function as shown in Figs. 3 - 5. However, to reach a better agreement with the bulk of experimental data, the ENDF/B-VIII.0 evaluation was scaled up by factor 1.10. In the second run, the ENDF/B-VIII.0 prior was replaced by output from the GMA fit.

The evaluation of the ^{7}Li(n,n'γ) cross section by the GMA code was performed in the energy range 0.7 to 17 MeV to avoid the impact of too low and very scattered experimental data near reaction threshold and at higher energies. The energy grid for this fit was selected with a step 0.05 MeV from 0.7 to 1.3 MeV, 0.10 MeV to 4.5 MeV, 0.25 MeV to 9 MeV and 0.50 MeV up to 17 MeV, that yields in total 78 energy nodes.

TABLE 2. EXPERIMENTS SELECTED FOR EVALUATION OF THE ^{7}Li(n,n'$\gamma_{478\ \mathrm{keV}}$) CROSS SECTION.

No.	Author, Year.	Type of Cross Section	Neutron Energies	Number of Points	Relative Weight
1	Benveniste, 1962	absolute	13.5 - 15.0 MeV	4	0.006
2	Western, 1965	absolute	14.5 MeV	1	0.006
3	Presser, 1972	absolute	0.95 – 5.0 MeV	42	0.004
			4.8 – 8.75 MeV	17	0.004
			5.0, 5.25 MeV	2	0.004
			19.0 – 20.0 MeV	4	0.002
4	Dickens, 1974	absolute	0.65 - 20 MeV	75	0.002
5	Smith, 1976	abs ratio	0.65 - 4.0 Me	20	0.016
6	Morgan, 1978	absolute	0.65 - 20 Me	78	0.008
7	Olsen, 1980	absolute	0.65 – 5.5 MeV	32	0.015
8	Nyman, 2016	absolute	0.65 – 17 MeV (100 m)	69	0.050
			0.65 – 16 MeV (199 m)	54	0.054
9	Nelson, 2018	absolute	0.85 – 17 MeV	43	0.020
10	Batchelor, 1963	absolute	1.5, 3.4, 4.0 MeV	2	0.008
11	Knitter, 1968	absolute	1.1 – 2.3 MeV	8	0.018
12	Knox, 1978	absolute	2.3 – 4.1 MeV	5	0.009
	Total		***0.70 – 17.0 MeV***	***452***	

The results of the GMA fit to the selected experimental data are depicted in Figs. 3 to 5 to show the detailed behaviour in three energy intervals: 0.7 - 12 MeV (maximal values of the cross section), 0.55 – 1.10 MeV (increase above (n,n') reaction threshold) and 8 - 21 MeV (decreasing part). The bottom inserts in these Figs. show the evaluated uncertainties which reach a minimum value of ≈ 2% at neutron energies between 0.7 and 8 MeV. The overall fitting parameter, chi-squared χ^2, equals 1.69.

As a reference cross section for practical use, we recommend the GMA evaluation from 0.9 to 8 MeV where the cross section value is larger than half of plateau value and uncertainty is close to minimum value. Table 3 lists the recommended cross section and relative uncertainty.

The energy-energy correlation matrix for the evaluated cross section is plotted in Fig. 6 showing the moderate (≈ 0.5) energy-energy correlation covering the whole energy range.

The evaluated cross section and covariance matrix is also available as ENDF-6 formatted files MF3 and MF33.

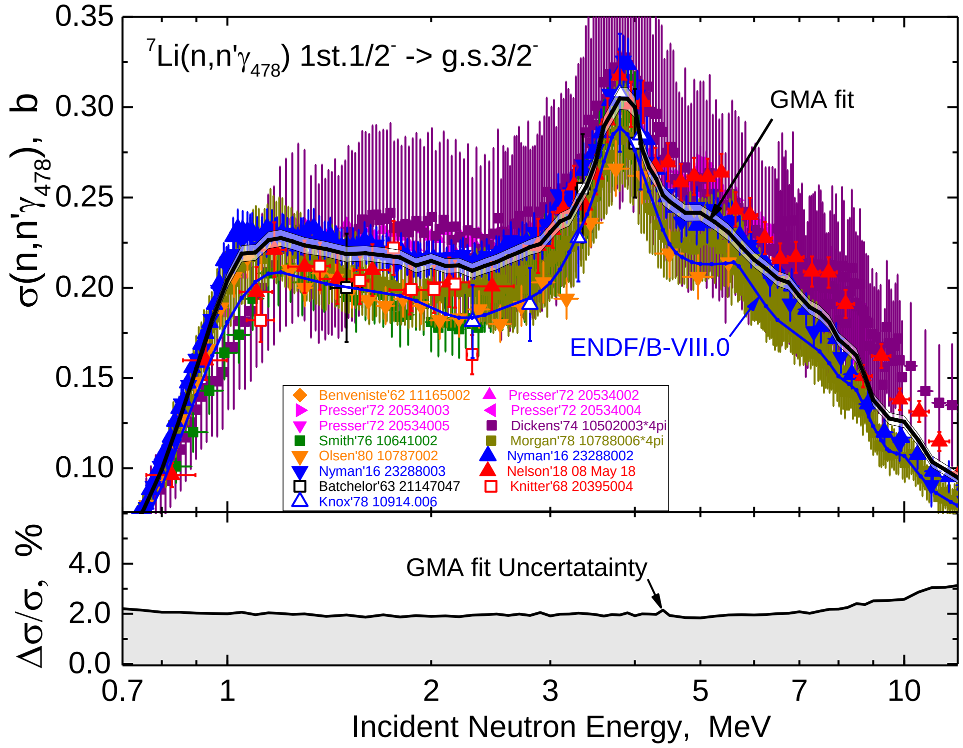

FIG. 3. ⁷Li(n,n'γ) reaction cross section in the neutron energy range 0.7–12 MeV. Top: existing and selected experimental (n,xγ) and (n,n₁) data (symbols); GMA fit (black curve) and ENDF/B-VIII.0 evaluation (blue). Bottom: uncertainty of the GMA fit.

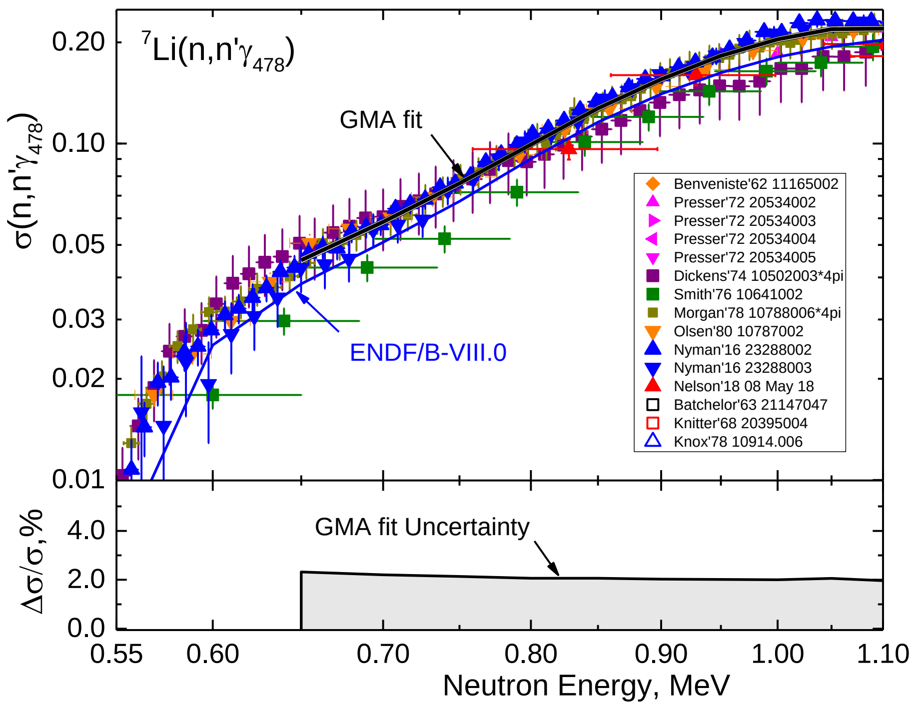

FIG. 4. The same as in Fig. 3, but for the neutron range from reaction threshold up to 1.10 MeV.

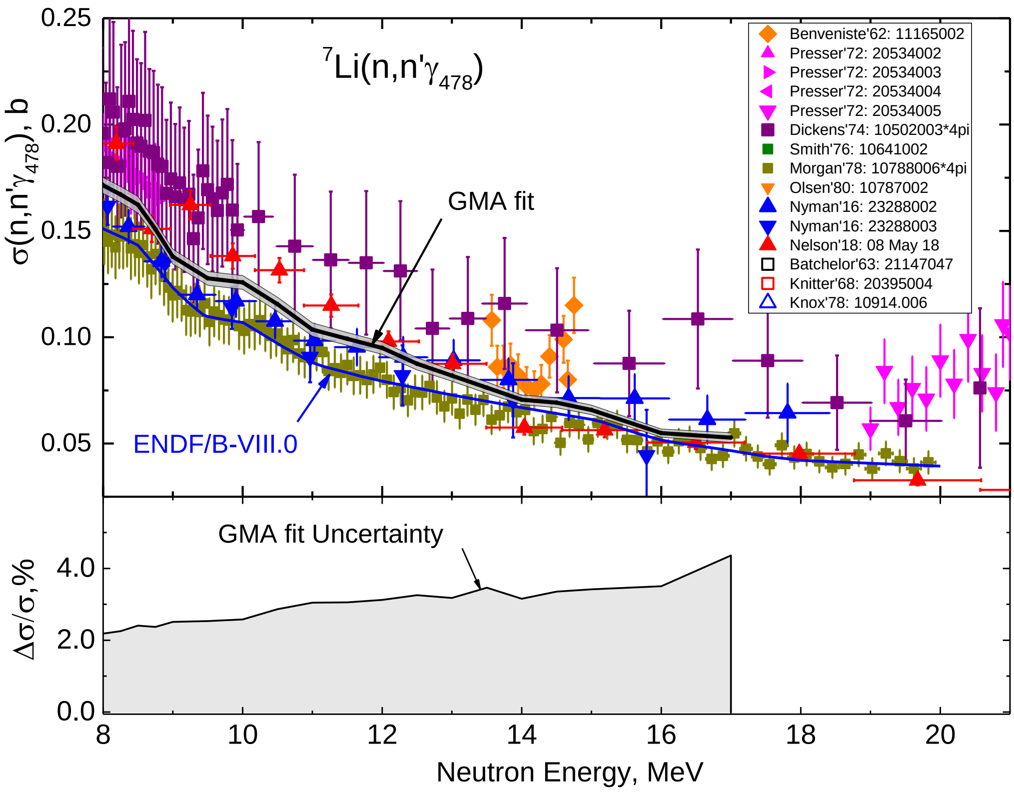

FIG. 5. The same as in Fig. 3, but for the neutron range from 8 to 21 MeV.

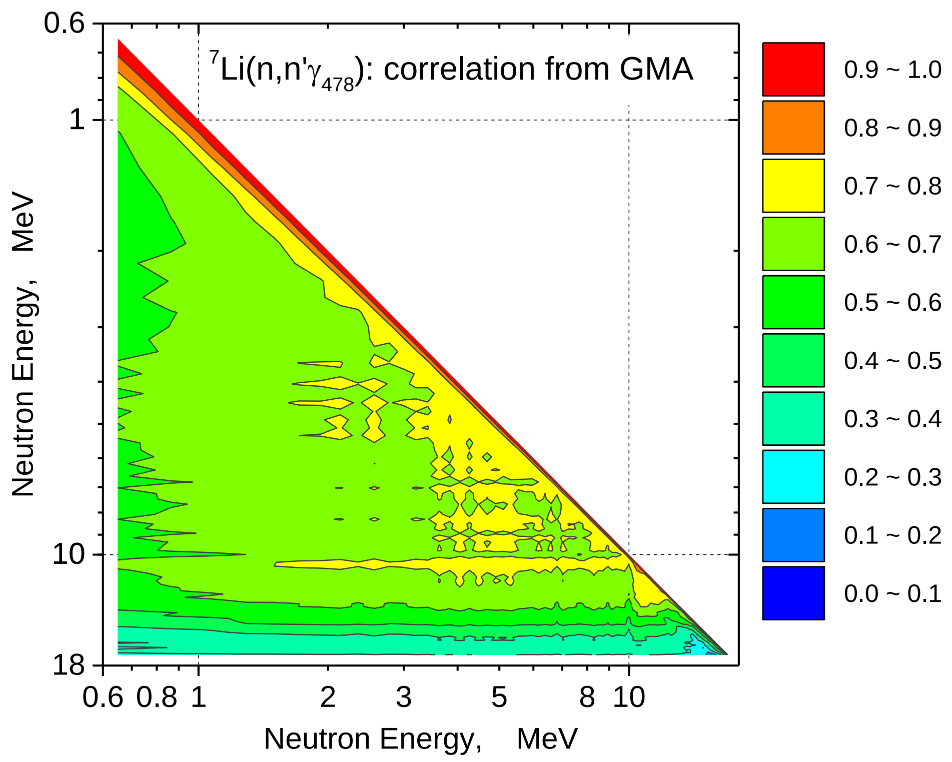

FIG. 6. Energy-energy correlation matrix from the GMA fit in the neutron energy range 0.7 – 17 MeV.

TABLE 3. RECOMMENDED EVALUATED ^{7}Li(n,n'$\gamma_{478\ \mathrm{keV}}$) CROSS SECTION.AND RELATIVE UNCERTAINTY.

E, MeV	σ(E), b	Δσ(E)/σ(E), %	E, MeV	σ(E), b	Δσ(E)/σ(E), %
0.90	0.155	2.02	3.30	0.248	2.03
0.95	0.182	2.02	3.40	0.256	2.00
1.00	0.204	2.00	3.50	0.268	1.97
1.05	0.220	2.06	3.60	0.289	1.91
1.10	0.218	1.97	3.70	0.295	1.97
1.15	0.226	2.04	3.80	0.304	1.95
1.20	0.228	2.02	3.90	0.304	2.04
1.25	0.225	1.97	4.00	0.301	1.92
1.30	0.223	1.99	4.10	0.275	2.00
1.40	0.222	1.90	4.20	0.266	1.99
1.50	0.218	1.96	4.30	0.261	1.98
1.60	0.219	1.87	4.40	0.251	2.15
1.70	0.218	1.96	4.50	0.248	1.93
1.80	0.217	1.87	4.75	0.241	1.85
1.90	0.211	1.93	5.00	0.242	1.84
2.00	0.216	1.90	5.25	0.236	1.90
2.10	0.212	1.92	5.50	0.230	1.95
2.20	0.213	1.89	5.75	0.222	1.97
2.30	0.209	1.95	6.00	0.215	1.96
2.40	0.212	1.96	6.25	0.211	1.97
2.50	0.214	1.99	6.50	0.205	2.01
2.60	0.217	1.94	6.75	0.204	2.02
2.70	0.220	1.99	7.00	0.195	2.08
2.80	0.223	1.93	7.25	0.189	2.02
2.90	0.224	2.05	7.50	0.186	2.10
3.00	0.231	1.91	7.75	0.181	2.18
3.10	0.237	1.99	8.00	0.171	2.18
3.20	0.238	1.99			

4. Conclusions

The experimental data relevant for evaluation of the ^{7}Li(n,n'γ_{487}) cross sections were collected and reviewed critically. In total, 14 experiments where outgoing gammas were detected, and 5 experiments where scattered neutrons exciting the 487 keV state in ^{7}Li were registered, are known of.

These measurements were analysed from the view of the descriptive documentation availability, measuring technique, samples used, applied corrections, and completeness of reported uncertainties. For the evaluation we selected data from 12 experiments, omitting those carried out between 1955 – 1968 with massive samples, having large uncertainties or disagreeing with the majority of accumulated results. It should be noted that the recent experiments which provided data with the lowest uncertainties have most essential impact on the evaluation.

The non-model evaluation of the ^{7}Li(n,n′γ_{487}) cross section has been performed by the GMA code. The 487 keV γ-ray production cross section was estimated from 0.65 up to 17 MeV with uncertainties of 2 - 4%, a full covariance matrix was also computed.

In the energy range from 0.9 to 8 MeV, where the cross section has a maximal value and minimal energy fluctuation, the ^{7}Li(n,n′γ_{487}) reaction could be recommended for inclusion in the standards with uncertainties of ≈ 2%.

Acknowledgment

The authors should like to thank M. Nyman and A. Plompen for providing detailed information about their measurements.

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Nuclear Data Section
International Atomic Energy Agency
Vienna International Centre, P.O. Box 100
A-1400 Vienna, Austria

E-mail: nds.contact-point@iaea.org
Fax: (43-1) 26007
Telephone: (43-1) 2600 21725
Web: http://www-nds.iaea.org