Karlsruhe Institute of Technology

Status and benchmarking of the deuteron induced Tritium and Beryllium-7 production cross sections in Lithium

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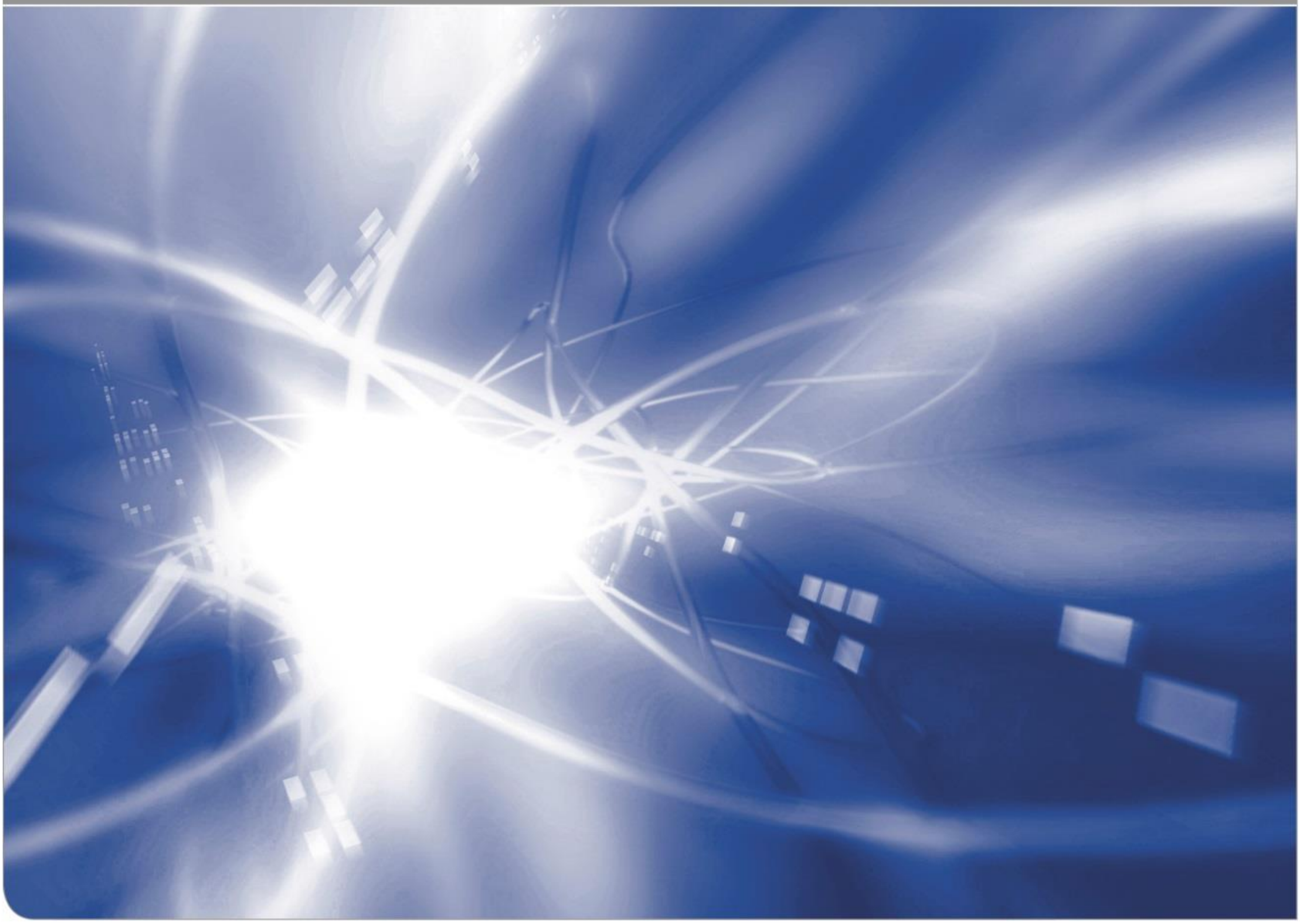

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1. INTRODUCTION

This report summaries the results of analyses of the available experimental and evaluated d-Li cross-section data for the assessment of the tritium and beryllium-7 production in IFMIF-DONES, the International Fusion Materials Irradiation Facility - DEMO Oriented Neutron Source project [1] which is a part of the European Fusion Roadmap [2]. The work comprises the collection and quality assessment of the relevant experimental cross-section data, comparison with available contemporary evaluations FZK-2005, ENDF/B-VIII.0, JEFF-3.3, TENDL-2017/2019, FENDL-3.1 and others. These evaluated cross sections were then used to calculate the radioactive inventories generated in the thick Li target with the help of the own developed code d-Activ and conventional inventory code FISPACT-II. Based on the outcomes of this analysis, we recommend which deuteron induced cross section as well as thick target yield data have to be additionally measured and which evaluated libraries can be presently used for the IFMIF-DONES inventory calculations.

In year 2004 we estimated the ^{3}H and ^{7}Be radioactive inventories caused by the deuterons and neutrons in the IFMIF lithium jet and Li quench tank [3], employing the d + $^{6,7}Li$ evaluated cross sections data from evaluations INPE-FZK-01 [4] and FZK-05 published in 2008 [5]. Since then the new versions of major evaluated cross section libraries and several new experimental data have appeared that has stimulated us to recheck the status of relevant data and results of previous inventory calculations.

The next sections collect and discuss all available experimental and evaluated cross section data for the deuteron induced reactions on the lithium isotopes or natural element and validate them against the ^{3}H and ^{7}Be thick target radioactive yields.

2. DEUTERON INDUCED ^{3}H AND ^{7}BE PRODUCTION CROSS SECTIONS ON THE LI ISOTOPES

2.1 d-Li reaction channels and evaluated cross section data

Table 1 lists the reaction channels kinematically allowed for the deuteron collisions with lithium isotopes at incident energies up to 30 MeV, their Q values and reaction thresholds E_{thresh}. For convenient comparison with evaluated cross section files the MT numbers, unique reaction designations currently adopted in the ENDF-6 format [6] are also noted down there.

In this Table the tritium production channels are emphasized by bold blue font. It is seen that the d + ^{6}Li system has two tritium production channels both with zero-energy threshold but then no one opens until 21 MeV. The tritium generation in the deuteron interaction with ^{7}Li starts at $E_d \geq 1.217$ MeV, then additionally six channels open below 29 MeV.

The beryllium-7 production channels are emphasized by bold red font. Only reactions $^{6}Li(d,n)^{7}Be$ with zero threshold and $^{7}Li(d,2n)^{7}Be$ with E_{thresh} = 4.979 MeV will generate ^{7}Be until 50 MeV.

The major evaluated cross section libraries for the deuteron interaction with Li isotopes and origin of information there are listed in Table 2.

One of the first and independent evaluation up to deuteron energy E_d = 50 MeV, INPE-FZK-01, was done before 2001 in collaboration between INPE Obninsk and FZK Karlsruhe [4]. The updated version FZK-05 was published in 2008 [5], it was validated against neutron production channels and tuned to the need of the IFMIF d-Li neutron source modelling. It is worth to remind that these both libraries contain the cross sections for deuteron energies up to 50 MeV, whereas all others known at that time – only below 5 or 20 MeV and thus were not applicable for the IFMIF neutronics.

ENDF/B-VII.1 [7] library for d + ^{6}Li and d + ^{7}Li has adopted the Los Alamos laboratory evaluations released in 2004 - 2005 years and has covered the deuteron energies up to 5 MeV. The recent version of ENDF/B-VIII.0 released in 2018 [8] was updated only for the d + ^{7}Li reaction and extended its high energy limit to 20 MeV.

Table 1. The reaction channels for the deuteron interactions with lithium isotopes opened below 30 MeV, their Q values and kinematic thresholds E_{thresh}. The ^{3}H production channels are highlighted in blue bold front, ^{7}Be – in red. MT is the reaction type numbers adopted in ENDF-B6 format.

Reaction Products	Q, MeV	E_{thresh}, MeV	MT numbers
	deuterons incident on ^{6}Li		
2α	22.372	0.	
γ + ^{8}Be	22.281	0.	
p + ^{7}Li	5.027	0.	
n + ^{7}Be (g.s. + 0.429 MeV)	**3.382**	**0.**	**4 = 50+51**
p + t + α	**2.559**	**0.**	**116+112**
n + ^{3}He + α	1.795	0.	34
^{3}He + ^{5}He (→ n + ^{4}He)	1.060	0.	
t + ^{5}Li (→ p + ^{4}He)	**0.590**	**0.**	**105**
d + ^{6}Li	0.	0.	
2d + α	-1.474	1.968	
n + p + ^{6}Li	-2.225	2.969	
n + p + d + α	-3.699	4.937	
…	…	…	
d + t + ^{3}He	**15.794**	**21.083**	**182**
2p + 2t	**17.255**	**23.033**	
n + p + t + ^{3}He	**18.019**	**24.052**	**184**
n + t + ^{4}Li	**21.120**	**28.200**	**33**
….			
	deuterons incident on ^{7}Li		
γ + ^{9}Be	16.694	0.	
n + 2α	15.122	0.	
n + ^{8}Be (→ 2α)	15.029	0.	
α + ^{5}He (→ n + ^{4}He)	14.387	0.	
d + ^{7}Li	0.	0.	
n + ^{8}Be (→ 2α)	15.029	0.	
α + ^{5}He (→ n + ^{4}He)	14.387	0.	
d + ^{7}Li	0.	0.	
p + ^{8}Li	-0.192	0.247	
t + ^{6}Li	**-0.994**	**1.279**	**105 (700 +)**
n + p + ^{7}Li	-2.225	2.863	
d + t + α	**-2.468**	**3.176**	**117**
2n + ^{7}Be (g.s. + 0.429 MeV)	**-3.869**	**4.979**	**16**
^{3}He + ^{6}He	-4.480	5.767	
n + p + t + α	**-4.692**	**6.038**	**45**
p + t + ^{5}He (→ n + ^{4}He)	**-5.427**	**6.990**	**116**
…	**…**	**…**	
p + α + ^{4}H (→ n + ^{3}H)	**-6.290**	**8.100**	**112**
n + t + ^{5}Li (→ p + ^{4}He)	**-6.660**	**8.570**	**33**
2t + ^{3}He	**-16.788**	**21.607**	
p + d + 2t	**-22.281**	**28.678**	**115**
…			

Table 2. Major evaluated cross sections libraries for the deuteron interaction with Li isotopes and an origin of information there.

Evaluation	Release Year	Origin of Evaluation; High Energy Limit	
		d + ^{6}Li	d + ^{7}Li
FZK-05	2005	update, 50 MeV	update, 50 MeV
INPE-FZK-01	2001	new, 50 MeV,	new, 50 MeV
ENDF/B-VIII.0	2018	ENDF/B-VII.1; 5 MeV	update: 20 MeV
ENDF/B-VII.1	2011	LANL 2004; 5 MeV	LANL 2006; 20 MeV
TENDL-2019	2019	ENDF/B-VII.1; 5 MeV	ENDF/B-VII.1; 20 MeV
TENDL-2017	2017	ENDF/B-VII.1; 5 MeV	ENDF/B-VII.1; 20 MeV
TENDL-17(162g)	2017	TALYS-1.9; 1000 MeV	TALYS-1.9; 1000 MeV
FENDL-3.1	2011	TALYS-1.4; 200 MeV	TALYS-1.4; 200 MeV
JEFF-3.3	2018	ENDF/B-VII.1; 5 MeV	ENDF/B-VII.1; 20 MeV
JENDL	-	no evaluation	no evaluation

The recent and latest libraries TENDL-2017 [9] as well as TENDL-2019 [10] have accepted the evaluated files from ENDF/B-VII.1. Designated in the present report as TENDL-17(162g) is a deuteron-induced reaction sub-library provided in the 162 energy groups up to 1000 MeV for the use with inventory code FISPACT-II [11]. Its content turns out to be different from TENDL-2017 probably due to inclusion of additional tritium production reaction channels from the TALYS modelling or FENDL deuteron sub-library.

The Fusion Evaluated Nuclear Data Library FENDL-3.1 (the latest version 3.1d was issued in Sep 2018) [12] is identical to FENDL-3.0 for the case of deuteron induced reactions on the Li isotopes. The latter was generated in 2011 with the help of the reaction cross section modelling code TALYS (version 1.4) up to 200 MeV. To extract the ^{3}H and ^{7}Be production cross sections from the ENDF-6 formatted FENDL-3.1 files we used the processing code NJOY21 [13]. For the convenience of data plotting and reduction, the FENDL-3.1 cross sections were also represented in the 162 energy group format or similarly to TENDL-17(162g).

The latest version of Joint Evaluated Fission and Fusion File (JEFF-3.3) [14] was released in 2018 and has adopted the d + ^{6,7}Li reactions files from ENDF/B-VII.1.

The Japanese Evaluated Nuclear Data Library JENDL has no evaluation for deuteron induced reactions yet, however the release of the JENDL deuteron reaction sub-library JENDL/DEU-2020 is expected in this year [15].

The reference handbook "Nuclear Physics Constants for Thermonuclear Fusion" issued in 1989 [16] contains a comprehensive overview of the nuclear reaction cross-sections for the interaction of hydrogen and helium isotopes with light nuclei up to boron. The authors have fitted the spline functions to the large body of experimental information on integral and partial differential cross-sections available at that time. The electronic version (SaBa) of this evaluated experimental database was issued in 1991 taking into account the new experimental data, revealed errors and misprints [17]. Regrettably but the package SaBa was not available for us. Thus we took, when it was possible, the evaluated cross sections for the reactions of our interest from equations or tables given in Handbook [16] (and labelled them in Figures as "Handbook-89"). As a rule, this evaluation agrees with experimental data available now but it covers the deuteron energy range up to ≈ 4 - 17 MeV.

Fig. 1 depicts the deuteron induced cross sections for all reaction channels on elemental lithium from evaluation FZK-05 as a function of deuteron energy to compare their values and energy dependences.

It is seen that probability of the tritium and beryllium-7 production is relative small in comparison with other deuteron induced reaction channels, in particular with the neutron, helium or proton generation.

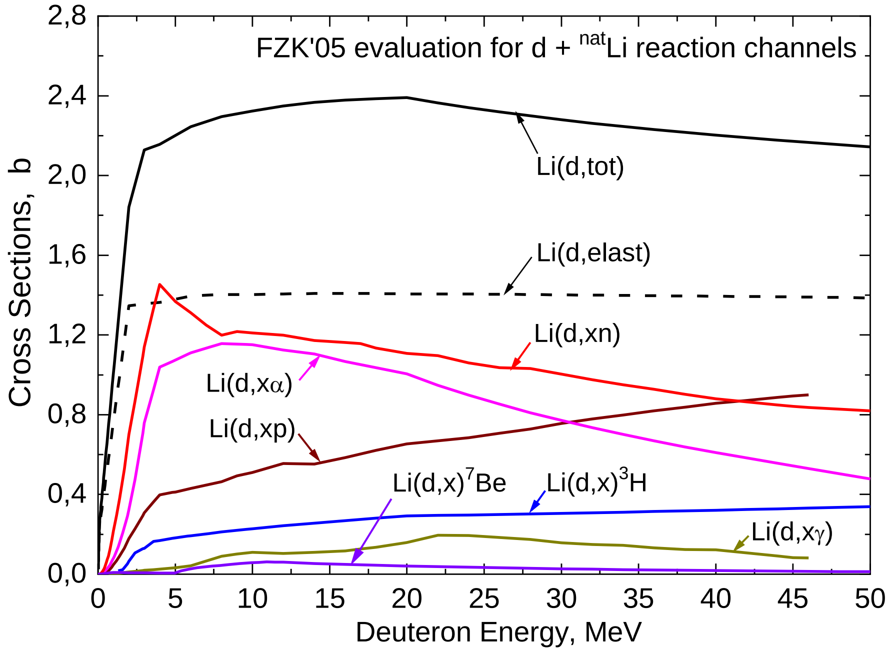

Fig. 1. Cross sections from FZK-05 for the most substantial channels of the d + ^{nat}Li reaction.

2.2 Status of the Tritium production cross section data.

The experimental cross sections data relevant to the deuteron-induced ^{3}H and ^{7}Be production reactions were searched and taken from the EXFOR database [18] and literature. If the numerical data were not included in EXFOR yet we have digitized the published figures, as was in the case [36, 41]. Table 3 lists 28 found and relevant experiments. They are grouped according to the experimental methods used for detection of reaction products:

- activation, i.e. detecting the radiation from decaying isotopes ^{3}H or ^{7}Be by scintillation or semiconductor detectors;
- charged particle spectrometry of tritons or beryllium-7 by silicon surface-barrier detector (SSD);
- neutron time of flight (TOF) spectrometry by scintillation detector.

Figs. 2 - 3 compare the **<u>tritium production cross sections on the ^{6}Li and ^{7}Li isotopes</u>** from published measurements and considered evaluations. It is seen that rather few experiments [20, 27, 32] have used the activation tritium counting technique and thus did report the total tritium production (d,xt) from all reaction channels. They were carried in the period 1954 to 1997, the measured cross section data are available only up to 8 MeV, substantially fluctuate and have large uncertainties in the energy interval from ≈ 5 to 8 MeV.

Besides the tritium activity counting experiments, several others [36 - 47] have used the surface-barrier detectors to record the energy and angular distributions of the outgoing triton ions, see Table 3. In the practice, such t-spectrometry technique was used to measure only the yield of discrete energy tritons (d,t_i) which leave the residual nucleus in the ground or in the first (seldom, higher) excited states U_i. Moreover the discrete tritons were not registered in whole emission angle range. The continuum energy spectra of tritons were measured neither in whole energy range nor at sufficient set of angles.

Table 3. Overview of the experiments which report the cross section relevant to the ^{3}H and ^{7}Be production in the deuteron induced reactions on the Lithium isotopes.

First Author, Year	Reaction	E_d range, MeV	Additional information	Ref.
Activation technique: counting the decaying isotope ^{3}H				
Macklin, 1959	$^{6}Li(d,x)^{3}H$ $^{7}Li(d,x)^{3}H$	0.38 – 3.92 1.28 – 4.14		[20]
Holland, 1979	$^{6}Li(d,x)^{3}H$	0.12 – 0.77		[27]
Abramovich, 1997	$^{6}Li(d,x)^{3}H$ $^{7}Li(d,x)^{3}H$	1.70 – 7.30 1.70 – 7.30		[32]
Triton SSD spectrometry technique: measurement of the energy-angular distribution of emitted ^{3}H ions (U_i denotes excitation energy of ^{5}Li or ^{6}Li)				
Levine, 1955	$^{7}Li(d,t_{0,1})^{6}Li^{*}$	14.4	$U_{0,1}$ = g.s., 2.19 MeV	[37]
Haffner, 1956	$^{7}Li(d,t_{0})^{6}Li$	15.0	U_0 = g.s.	[38]
Hamburger, 1960	$^{6}Li(d,t_{i-j})^{5}Li^{*}$ $^{7}Li(d,t_{2})^{6}Li^{*}$	14.7 14.8	U_{i-j} = 8.65 - 12.65 MeV U_2 = 3.57 MeV	[39]
Vlasov, 1960	$^{7}Li(d,t_{0,1,2})^{6}Li^{*}$	20.0	$U_{0,1,2}$ = g.s., 2.19, 3.58 MeV	[40]
Zander, 1971	$^{7}Li(d,t_{0})^{6}Li$	12.0	U_0 = g.s.	[41]
Mao, 1972	$^{6}Li(d,t_{0})^{5}Li$ $^{7}Li(d,t_{0})^{6}Li$	5.03 5.03	U_0 = g.s. $U_{0,1}$ = g.s., 2.18 MeV	[42]
Huang, 1974	$^{6}Li(d,t_{0})^{5}Li$ $^{7}Li(d,t_{0})^{6}Li$	3.7 3.7	U_0 = g.s. U_0 = g.s.	[43]
Gulamov, 1990	$^{7}Li(d,t_{0,1,2})^{6}Li^{*}$	18.0	$U_{0,1,2}$ = g.s., 2.45, 3.56 MeV	[44]
Wuosmaa, 2008	$^{2}H(^{7}Li,t_{0,1,2})^{6}Li^{*}$	32.1 (E_{Li7}= 87MeV)	$U_{0,1,2}$ = g.s., 2.45, 3.56 MeV	[45]
Burterbayev, 2015 Burterbayev, 2019	$^{7}Li(d,t_{0,1})^{6}Li^{*}$ $^{7}Li(d,t_{0})^{6}Li$	25.0 14.5	$U_{0,1}$ = g.s., 2.19 MeV U_0 = g.s.	[46] [47]
Generalov, 2019	$^{6}Li(d,t)$ $^{7}Li(d,t_{0,1})$	3.50 – 8.00 4.00 – 10.0	U_0 = g.s	[36]
Activation technique: counting the decaying isotope ^{7}Be				
Hirst, 1954	$^{6}Li(d,n)^{7}Be$	0.11 – 0.34		[19]
Szabo, 1977	$^{6}Li(d,n)^{7}Be$	0.10 – 0.18		[24, 25]
Ruby, 1979	$^{6}Li(d,n)^{7}Be$	0.30 – 0.93		[26]
Guzhovskij, 1980	$^{6}Li(d,n)^{7}Be$ $^{7}Li(d,2n)^{7}Be$	1.28 – 11.93 5.38 – 11.94		[28]
Vysotskij, 1990	$^{6}Li(d,n)^{7}Be$ $^{7}Li(d,2n)^{7}Be$	4.80 – 13.45 5.50 – 13.15		[29]
Hagiwara, 2011	$^{nat}Li(d,x)^{7}Be$	6.79 – 39.30		[34]
Generalov, 2017	$^{6}Li(d,n)^{7}Be$ $^{7}Li(d,2n)^{7}Be$	2.15 – 9.78 4.96 – 9.78		[35]
Proton SSD spectrometry technique: measurement of the energy-angular distribution of emitted protons from $^{6}Li(d,p_{0,1})^{7}Li^{*}$ and 0.477 MeV γ-ray from decay of $^{7}Li^{*}$(U_1 = 0.477 MeV)				
McClenahan, 1975	$^{6}Li(d,n_{0,1})^{7}Be^{*}$	0.49 – 2.92	^{7}Be: $U_{0,1}$ = g.s., 0.43 MeV	[21]
Neutron TOF spectrometry technique: measurement of the energy-angular distribution of secondary neutrons (U_i denotes excitation energy of ^{7}Be)				
Azimov, 1975	$^{6}Li(d,n_{0,1})^{7}Be^{*}$	15.25	$U_{0,1}$ = g.s., 0.43 MeV	[22]
Elvin, 1977	$^{6}Li(d,n_{0,1})^{7}Be^{*}$	0.20 – 0.88	$U_{0,1}$ = g.s., 0.43 MeV	[23]
Bochkarev, 1990	$^{6}Li(d,n_{0,1})^{7}Be^{*}$	0.80 – 12.10	$U_{0,1}$ = g.s., 0.43 MeV	[31]
Hofstee, 2001	$^{6}Li(d,n)^{7}Be$	0.31		[33]
^{7}Be recoil spectrometry technique: measurement of the angular distribution of $^{7}Be^{*}$ excited to U_i				
Gangadharan, 1970	$^{6}Li(d,n_{0,1})^{7}Be^{*}$	12.0 – 17.0	$U_{0,1}$ = g.s., 0.43 MeV	[30]

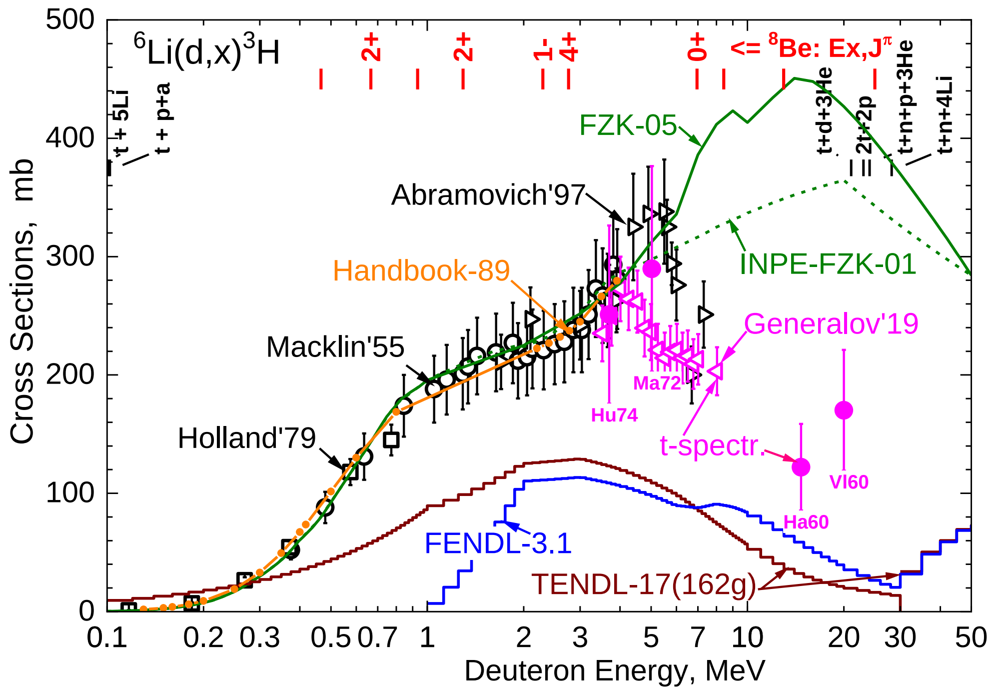

Fig. 2. Tritium production cross section for the d + ^{6}Li reaction. Experimental data: measured by activation are black symbols; summed discrete tritium production measured by t-spectroscopy - pink circles. Evaluated data are curves: FZK-05 (green), INPE-FZK-01 (dashed green), TENDL-17(162g) (wine), FENDL-3.1 (blue) and Handbook-89 (orange). The reaction channels energy thresholds are shown by vertical bars with corresponding notations. The deuteron energies corresponding the excited states (*Ex, J$^{\pi}$*) in ^{8}Be [49] are shown in red.

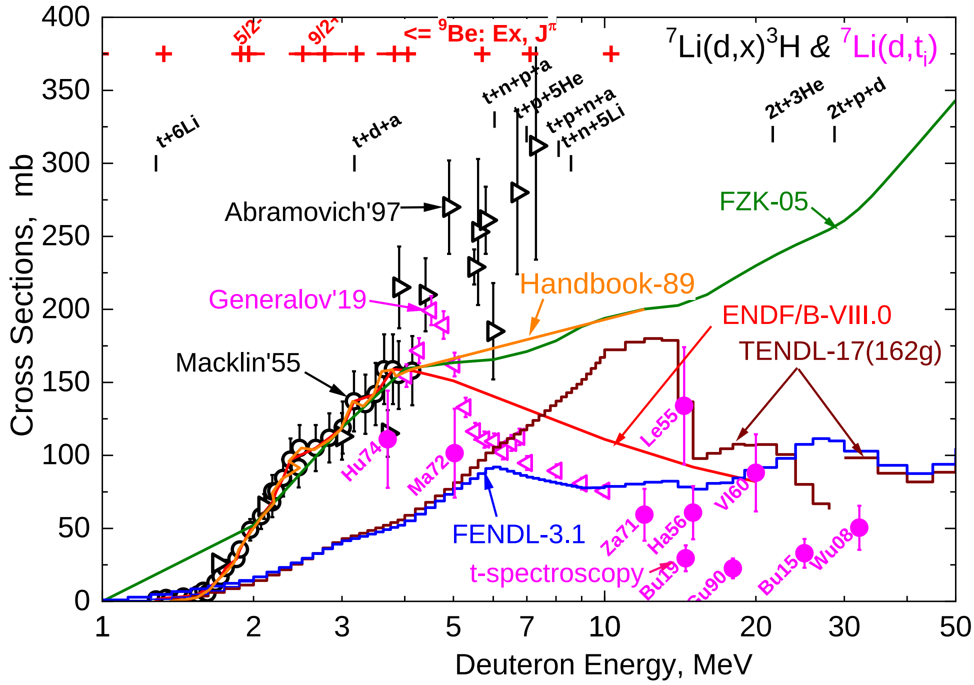

Fig. 3. Tritium production cross section for the d + ^{7}Li reaction. Experimental data: measured by activation are black symbols; summed discrete t-production measured by t-spectroscopy - magenta symbols. Evaluated data are curves: FZK-05 (green), ENDF/B-VIII.0 (red), TENDL-17(162g) (wine), FENDL-3.1 (blue) and Handbook-89 (orange). The reaction channel energy thresholds are shown by vertical bars with corresponding notations. The deuteron energies corresponding the excited states (*Ex, J$^{\pi}$*) in ^{9}Be [50] are shown in red.

We integrated the reported experimental angular distributions and summed discrete groups to get at least a part of the total tritium emission cross sections. Because of this procedure, the original uncertainties were additionally increased by 30%. The obtained cross sections from the t-spectrometry experiments are also plotted in Figs. 2 and 3. It is seen their results are close to the total tritium production cross section at low incident deuteron energies $E_d \approx 3 - 5$ MeV. Above this energy the existing t-spectrometry experiments essentially underestimate (d,xt) cross section since they miss the population of the higher bound and unbound levels in the reaction residuals.

It is interesting to note that Wuosmaa and co-workers [45] have irradiated deuterium target at rest by the ^{7}Li ions with energy 87 MeV. The corresponding energy of deuterons incident on the ^{7}Li target was calculated to be E_d = 32.1 MeV. The experiment of Gangadharan et al. [30] is unique one, in which the heavy recoil ^{7}Be*, associating the neutron emission from reaction ^{6}Li(d,n), was registered by the SSD spectrometer.

Among the evaluated libraries, only FZK-05 (and Handbook-87 [16]) predict rather precisely the measured (d,xt) cross section observed for both lithium isotopes up to 4 - 5 MeV. At higher energies the absence of the experimental data leaves the validation issue without answer. FZK-05 underestimates the single Abramovich' set for the ^{6}Li(d,xt) cross section, but is still closer to it than other evaluations.

ENDF/B-VIII.0 evaluation for the d + ^{6}Li system has no tritium production data in sections MT105, MT116 and MT112, which correspond to reactions ^{6}Li(d,t)^{5}Li, ^{6}Li(d,tpα) etc. For the deuteron interaction with ^{7}Li, it contains the cross section for ^{7}Li(d,t)^{6}Li(g.s.) (MT700) up to 20 MeV, which however shows a trend different from experiment already above 4 MeV. Among other evaluations, the ENDF is the only one which is based on an S-matrix analysis of experimental nuclear data for the two-body strong reactions leading to the intermediate states excitation at ≈ 20 - 40 MeV in ^{8}Be [48, 49] or ^{9}Be [50]. We have calculated and plotted in Figs. 2 and 3 the deuteron energies that correspond to these unbound levels at excitation energy E_x with spin and parity J^{π}. Comparing them and oscillations for the ^{6}Li(d,xt) and ^{7}Li(d,xt) cross sections observed by Abramovich et al. [32] at E_d = 4 - 8 MeV it is difficult to conclude whether they indeed correlate.

Both TENDL-17(162g) and FENDL-3.1 substantially underestimate the measured data. It is necessary to note that we extracted the tritium production cross sections from TENDL-17(162g) for isotopes ^{6}Li and ^{7}Li below 30 MeV by summing data from MT sections of file MF3 which have tritium in the outgoing channel (see Table 1); above 30 MeV - they were derived from file MF10, section MT5 and proper residual isotope (1003) yields:

^{6}Li(d,xt) = MF3/(MT105 + MT33 + MT112 + MT116) + MF10/MT5/1003 ;

^{7}Li(d,xt) = MF3/(MT105 + MT33 + MT45 + MT112 + 2*MT115 + MT116 + MT117) + MF10/MT5/1003.

Finally it is important to underline that for deuteron energy above ≈ 8 MeV there are no measured data, i.e. all existing evaluations are not experimentally proved yet and hence their reliability is still questionable.

2.3 Status of the Beryllium-7 production cross section data

Isotope ^{7}Be is produced by the ^{6}Li(d,n)^{7}Be and ^{7}Li(d,2n)^{7}Be reactions which populate only the ground state and 1st excited level with energy U_1 = 0.429 MeV (the latter then immediately decays to g.s.). The second level of ^{7}Be with excitation energy 4.751 MeV is unbound and decays with emission of ^{3}He and ^{4}He. This explains the larger value of neutron generation cross section than beryllium-7 production on the lithium isotopes. Figs. 4 and 5 compare the evaluated data with measured ones [19 - 35] found in EXFOR (see also Table 3).

For the ^{6}Li(d,n)^{7}Be reaction there are known eleven measurements which cover the deuteron energy range from 0.1 to 17 MeV, Fig. 4. Such large interest to this reaction, in particular in the hundreds keV-energy range, is caused by the importance for the understanding the stellar and big-bang nucleosynthesis of ^{7}Be as well as the advanced d + ^{6}Li fusion plasma fuel cycles.

Seven of these experiments have employed the activation technique, i.e. counting the 477 keV γ-rays which follow the decay of the ^{7}Be isotope with half-life period $T_{1/2}$ = 53.22 days. It has to be noted that J. Szabo et al. [24, 25] have primarily measured the thick target yields (TTY), which were regrettably not published and compiled in EXFOR. The authors then have derived the reaction cross section by differentiating the measured TTY. At energies 5 - 6 MeV data of O. Vysotskij et al. [29] systematically underestimate the ^{6}Li(d,n)^{7}Be reaction excitation function stipulated by all other experiments.

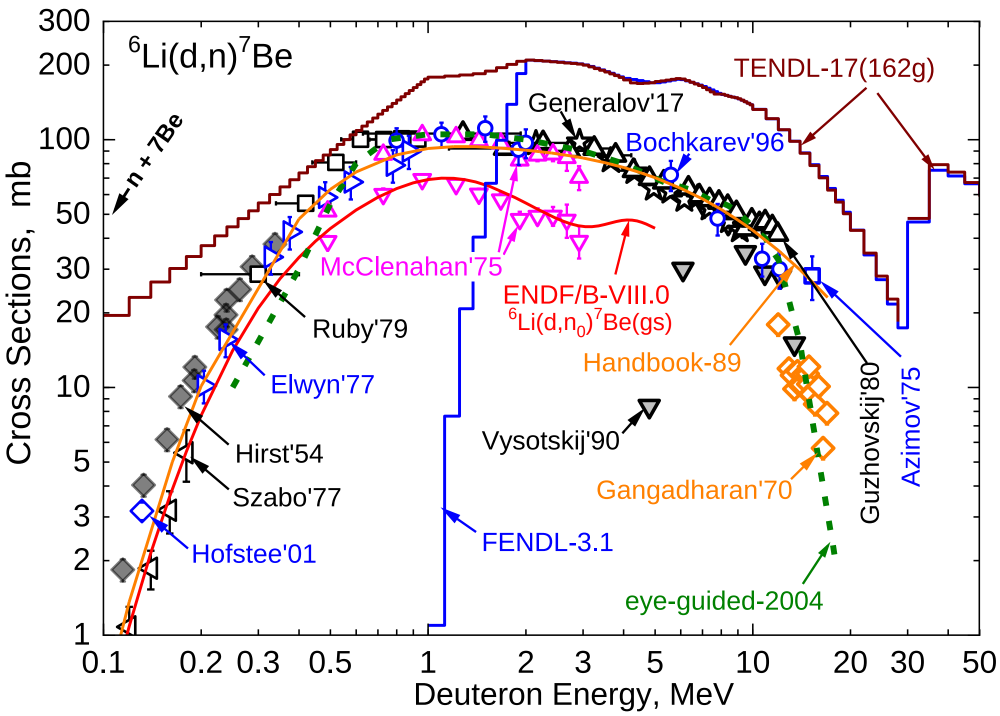

Fig. 4. Beryllium-7 production cross sections for the d + ^{6}Li reaction. Experimental data measured by activation are black symbols; summed discrete neutron production measured by TOF - blue symbols; proton or recoil spectrometry - magenta and orange symbols. Evaluated data are curves: eye-guided-2004 [3] (dashed green), ENDF/B-VIII.0 (red), TENDL-17(162g) (wine). FENDL-3.1 (blue) and Handbook-89 (orange). The reaction channel energy thresholds are shown by vertical bars with corresponding notations.

The other group of four experiments [22, 23, 31, 22] have used the TOF neutron spectrometry to measure the discrete neutrons from ^{6}Li(d,n$_0$+n$_1$)^{7}Be* which leave ^{7}Be in the ground and first excited states, thus separating them from "neutron continuum" or total neutron production.

McClenahan and Sege [21] have inferred the ^{6}Li(d,n$_{0,1}$)^{7}Be* cross sections from the mirror ^{6}Li(d,p$_{0,1}$)^{6}Li* reaction cross sections measured by the proton SSD technique and from the experimentally determined ratio of the 0.428 MeV (1st level of ^{7}Be) to the 0.477 MeV (1st level of ^{6}Li) γ-ray yields by a Ge(Li) detector.

S. Gangadharan and R. Wolke [30] carried out a unique experiment measuring the angular differential cross sections of the ^{7}Be* recoils in the ground and the first excited states from reaction ^{6}Li(d,n)^{7}Be at deuteron energies 12 to 17 MeV. The derived angular-integrated cross sections plotted in Fig. 4 confirm the sharp drop of the ^{6}Li(d,n)^{7}Be cross section above 12 MeV measured by Vysotskij [29] and Bochkarev [31] who employed different techniques.

Neither the FZK-05 nor FZK-01 evaluations have cross section for the ^{6}Li(d,n)^{7}Be reaction. In year 2004 an eye-guide curve was drawn through the experimental data in energy range from 0.3 to 20 MeV [3], as shown in Fig. 4, and was used for inventory calculations.

ENDF/B-VIII.0 contains only cross section for the ^{6}Li(d,n$_0$)^{7}Be(g.s.) reaction (MT50) which populates the ^{7}Be ground state. Due to this reason it agrees well with McClenahan experimental data for the same partial reaction ^{6}Li(d,n$_0$)^{7}Be(g.s.) but underestimates the total beryllium-7 production. It worth to note that McClenahan data for ^{6}Li(d,n$_{0+1}$)^{7}Be tolerably agree with other experiments.

The fit from Handbook-87 [16] to the experimental data existed at that time rather well reproduce all known measurements until 10 MeV.

The ^{7}Li(d,2n)^{7}Be reaction cross section were measured from threshold up to 13 MeV only by the activation technique in three experiments [28, 29, 35]. At higher energy there is a single measurement of M. Hagiwara and co-workers [34] but for the natural lithium. We divide his data by the ^{7}Li abundance 0.9241 to get an estimate for the ^{7}Li(d,2n)^{7}Be cross section, since above 10 – 12 MeV the ^{6}Li(d,n)^{7}Be cross section rapidly vanishes.

As seen in Fig. 5 the FZK-05 evaluation (and Handbook-87 [16]) reasonably agree with experimental data above reaction threshold up to 10 - 12 MeV, but at higher energies it slightly underestimates the results of M. Hagiwara and co-workers [34]. FZK-05 evaluation follows the ^{7}Li(d,2n)^{7}Be cross section from Handbook-87 [16] until 12 MeV.

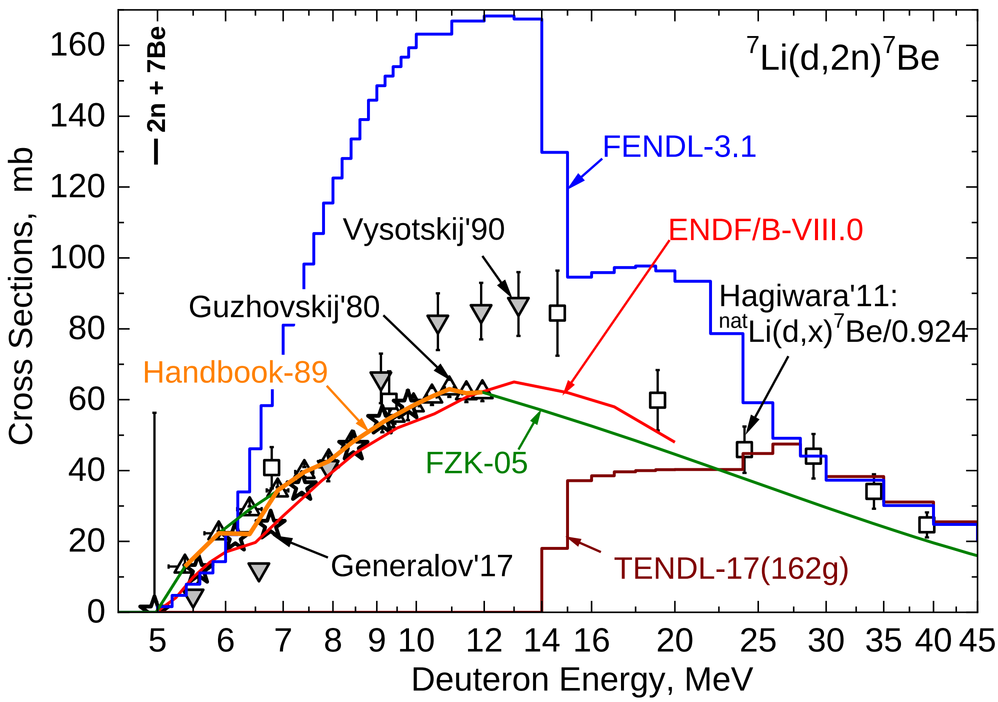

Fig. 5. Beryllium-7 production cross sections for the d + ^{7}Li reaction. Experimental data measured by activation are plotted as black symbols. Evaluated data are depicted as curves: FZK-05 (green), ENDF/B-VIII.0 (red), TENDL-17(162g) (wine), FENDL-3.1 (blue) and Handbook-89 (orange). The reaction channel energy thresholds are shown by vertical bars with corresponding notations.

TENDL-17(162g) represents the production of belylium-7 in the flowing MF files, MT sections and proper isotope (4007):

^{6}Li(d,x)^{7}Be = MF3/MT4 + MF10/MT5/4007 ;

^{7}Li(d,xt)^{7}Be = MF3/MT16 + MF10/MT5/4007 .

As seen in Figs. 4 and 5, TENDL-17(162g) overestimates the measured data for the $^{6}Li(d,n)^{7}Be$ reaction by factor 2, and lacks of $^{7}Li(d,2n)^{7}Be$ below 15 MeV.

The predictive quality of FENDL-3.1 for the ^{7}Be production reactions is also unacceptable for both lithium isotopes.

The ^{7}Be production cross section on elemental lithium ^{nat}Li(d,x)^{7}Be was measured only in the single experiment [34] however up to rather high energy 40 MeV. As seen in Fig. 6, the FZK-05 evaluation slightly underestimates these data, whereas the prediction quality of all others libraries is even worse. It has a sense to notice that reaction $^{6}Li(d,n)^{7}Be$ makes a dominant contribution at deuteron energies below 5 MeV, whereas reaction $^{7}Li(d,2n)^{7}Be$ - above this energy.

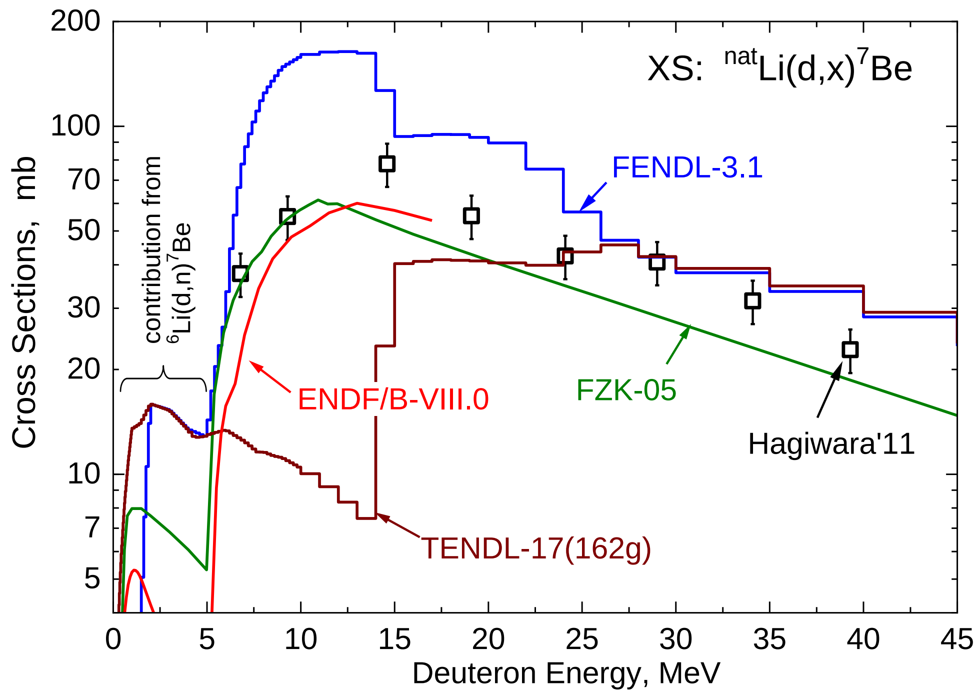

Fig. 6. Beryllium-7 production cross section for the d + ^{nat}Li reaction. Experimental data of M. Hagiwara et al. [34] are plotted as open symbols. Evaluated data - as curves: FZK-05 (green), ENDF/B-VIII.0 (red), TENDL-17(162g) (wine) and FENDL-3.1 (blue).

3. Deuteron induced ^{3}H and ^{7}Be inventory yields in the thick Li target

The calculation of the ^{3}H and ^{7}Be thick target yields (TTY) was performed in the two ways.

(1) The d-Activ code was developed to fold the $(d,x)^{3}H$ or $(d,x)^{7}Be$ evaluated cross sections on the Li isotopes with the deuteron energy losses in the natural lithium. The latter was taken from the Stopping and Range of Ions in Matter (SRIM) [51]. As seen in Fig. 7, for the deuteron energy below 50 MeV the electrical (i.e. atom ionization) losses dominate over nuclear ones (mostly elastic ion scattering).

(2) Code FISPACT-II [11] was also used in the present work to compute the ^{3}H and ^{7}Be inventories in the lithium media. The energy distribution of deuterons, needed for this purpose at each deuteron energy on the front Li target surface, was computed by the d-Activ code. The deuteron irradiation time was selected to be 1 hour, which is essentially lesser than the half-lives of ^{3}H ($T_{1/2}$ = 12.32 years) and ^{7}Be ($T_{1/2}$ = 53.22 days), so the decay of these inventories during an irradiation period is negligible.

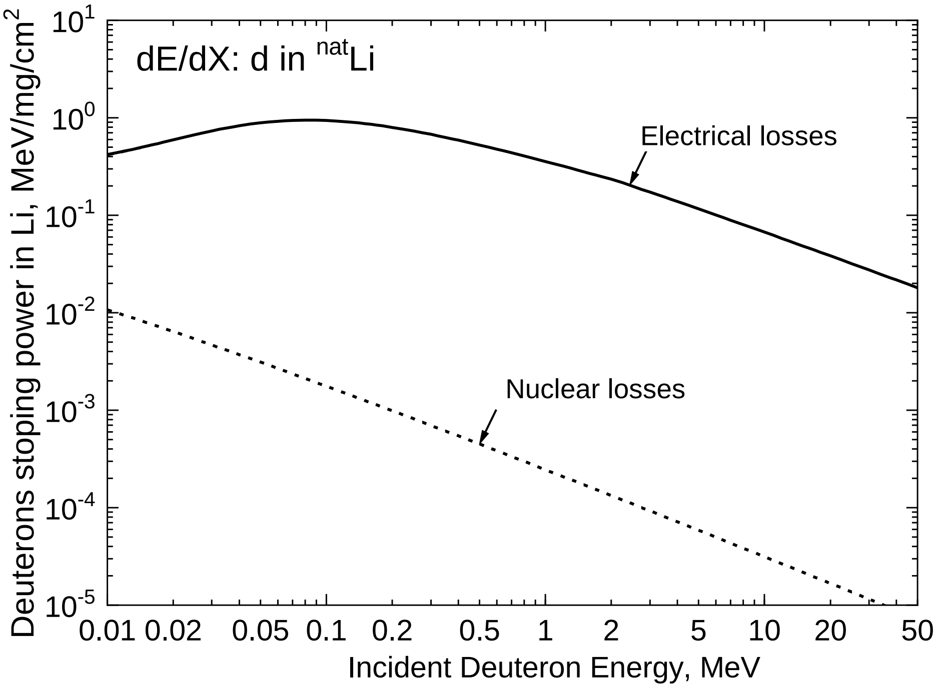

Fig. 7. Deuterons stopping powers in lithium from the SRIM database: electrical (solid curve) and nuclear (dashed) stoppings.

The calculated thick target yields are compared with experimental data [52 - 57] available in EXFOR in Figs. 8 and 9. It is important to stress that the tritium thick target yield was measured only in one experiment of U. von Möllendorff and co-workers at 40 MeV [56]. For the beryllium-7 inventory seven independent TTY measurements are available which cover the deuteron energies from 4 to 40 MeV and well agree each other. All experimental TTY data were obtained by activation technique.

The agreement between the results computed with codes d-Activ, FISPACT-II and McDeLicious [58], when the same d + ^{6,7}Li cross sections data are used, means the verification of these codes and input data preparation procedure.

It is seen that the FZK-05 evaluation reasonably reproduces the measured ^{3}H and ^{7}Be inventories in the thick lithium target that means a validation of this library against the existing deuteron energy integrated benchmarks. Calculations with natural and enriched lithium target by the d-Active code shows in Fig. 8 that reaction ^{7}Li(d,x)^{3}H makes a dominant contribution to the tritium production in natural lithium at all deuteron energies. Similarly, reaction ^{7}Li(d,x)^{7}Be defines the beryllium-7 inventories above 6 MeV, as seen in Fig. 9.

The tritium inventory in lithium is substantially underestimated by all other considered libraries ENDF/B-VIII.0, TENDL-17(162g) and FENDL-3.1, in particular at deuteron energy 40 MeV by factor 3.

The beryllium-7 inventory in lithium is reasonably reproduced by the ENDF/B-VIII.0 up to 20 MeV despite it lacks the ^{6}Li(d,x)^{7}Be cross section. The reason for this is a dominant contribution of reaction ^{7}Li(d,x) ^{7}Be to the TTY in the case of the natural lithium target.

TENDL-17(162g) wrongly predicts the ^{7}Be TTY dependence as a function of the deuteron energy, however gives a correct value at 40 MeV. FENDL-3.1 systematically overestimates the experimental ^{7}Be yield above 7 - 8 MeV.

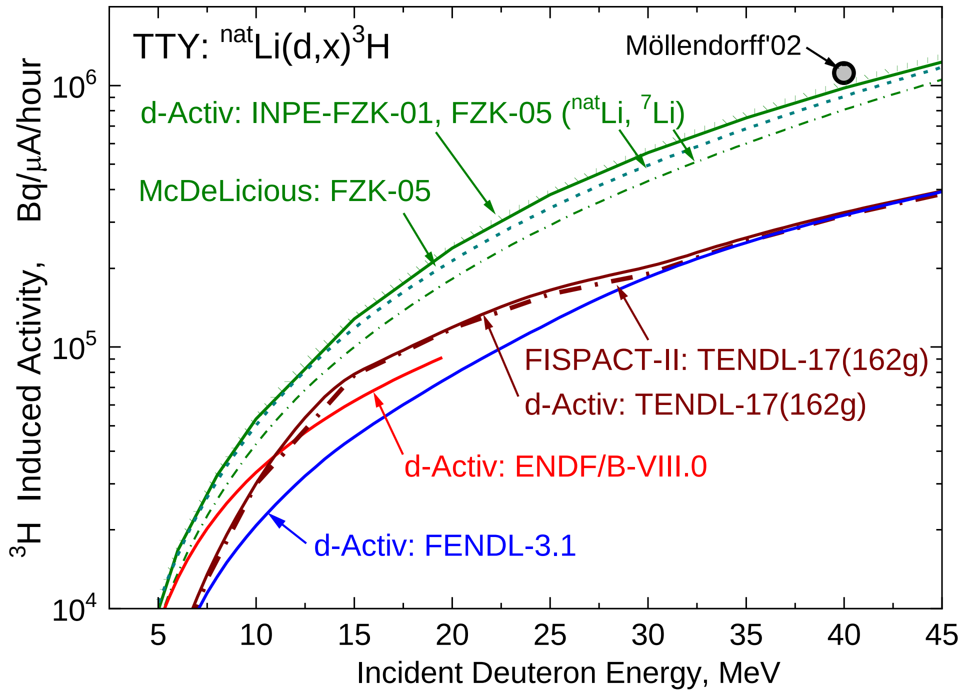

Fig. 8. Tritium thick target yield for deuterons incident on the natLi target. TTY from single experiment of U. von Möllendorff et al. [56] is shown by symbol ○. Curves are calculations carried out by different codes with the 6,7Li(d,xt) reaction cross sections from FZK-05 and INPE-FZK-01 (green), ENDF/B-VIII.0 (red), TENDL-17(162g) (wine) and FENDL-3.1 (blue).

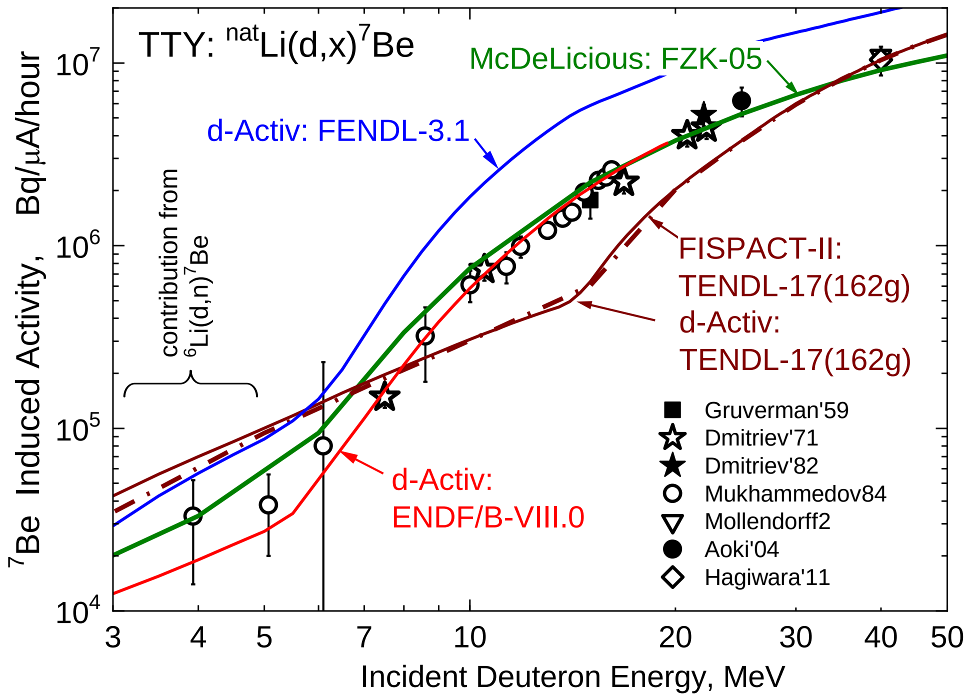

Fig. 9. Beryllium-7 thick target yield for deuterons incident on the natLi target. Experimental data available in EXFOR are shown by symbols. Curves are calculations carried out by different codes with the 6,7Li(d,xt) reactions cross sections from: FZK-05 (green), INPE-FZK-01 (dashed green), ENDF/B-VIII.0 (red), TENDL-17(162g) (wine) and FENDL-3.1 (blue).

5. Conclusions

Since 2004 the status of the experimental and evaluated data relevant to the tritium and beryllium-7 production cross sections or thick target yield induced by the fast deuterons in lithium changes as following.

Experimental data. Three new measurements of the ^{6,7}Li(d,n)^{7}Be cross sections from 2 to 10 MeV, ^{nat}Li(d,2n)^{7}Be from 6.8 to 39 MeV, ^{6}Li(d,t) and ^{7}Li(d,$t_{0,1}$) from 2.2 to 10 MeV have been carried out in Russian Federation and Japan. Regrettably but since 1997 there was no one new measurement of the total tritium production cross sections, that leaves reactions ^{6,7,nat}Li(d,xt) without any single experimental point at deuteron energies above ≈ 8 MeV. Similarly there are no experimental data for the tritium thick target yield since the year 2002 when pioneer and unique experiment of U. von Möllendorff and co-workers was carried out at single deuteron energy 40 MeV.

Traditionally the cross sections of the ^{6,7}Li(d,xt) reactions are compared and validated against the measurements which employed the tritium activity counting technique and thus delivered the total tritium production. In this work we also considered the tritons energy-angular distribution data measured by semiconductor detector. The latter were historically aimed on the detection and analysis of the partial (d,t_i) cross sections. However the extension of this technique to cover sufficient large range of the secondary energies and angles will deliver the (d,xt) data which will compliment those already obtained by activation technique. In particular, it is important at deuteron energy above 8 MeV where no activation measurements do exist so far.

Evaluations. New versions of cross section libraries ENDF, JEFF, TENDL (including the groupwise library TENDL-17(162g) for use with the FISPACT code) and FENDL were released last decade. However their prediction quality of the considered quantities in the deuteron induced reactions is still worse than FZK-05. The latter however lacks the cross section for the ^{6}Li(d,n)^{7}Be reaction channel.

The spline fits or tabulated data from the reference handbook “Nuclear Physics Constants for Thermonuclear Fusion” (Handbook-87) still reasonably predict the (d,x)^{3}H and (d,x)^{7}Be cross sections for deuteron energies up to 5 - 17 MeV.

Practical application, i.e. an assessment of radioactive inventories induced by deuterons in the lithium target used a neutron source. It was shown that usage of FISPACT-II with TENDL-17(162g) will underestimate the tritium inventory in thick lithium media at deuteron energy 40 MeV (an operation energy of the projected IFMIF or IFMIF-DONES facilities) by factor 3. The similar underestimation will be observed for the beryllium-7 inventory for deuteron energies between 10 and 25 MeV.

Briefly summarising we stress that measurements of the ^{6,7,nat}Li(d,xt) cross sections above 5 MeV and tritium thick target yields in lithium up to 40 MeV as well as the substantial upgrade of ENDF, JEFF, TENDL and FENDL are needed.

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