РОСАТОМ

ГОСУДАРСТВЕННАЯ КОРПОРАЦИЯ ПО АТОМНОЙ ЭНЕРГИИ «РОСАТОМ»

РФЯЦ ВНИИЭФ

$^{6}Li(d,p_0)^{7}Li$, $^{6}Li(d,p_1)^{7}Li^{*}$(0.478 МэВ), $^{6}Li(d,p_2)^{7}Li^{*}$(4.63 МэВ), $Li(d,p_4)^{7}Li^{*}$(7.46 МэВ), $^{6}Li(d,n_0)^{7}Be$, $^{6}Li(d,n_1)^{7}Be^{*}$(0.429 МэВ), $^{6}Li(d,n_2)^{7}Be^{*}$(4.57 МэВ), $^{6}Li(d,n_4)^{7}Be^{*}$(7.21 МэВ), $^{6}Li(d,x)^{7}Be$ REACTION CROSS SECTION

Generalov L.N., Zherebtsov V.A., Selyankina S.M.

71st meeting on nuclear spectroscopy and atomic nucleus structure «Nucleus-2021»

Online-conference, 20-25 September

MOTIVATION

- **Appearance of our $^{6}Li(d,p_{0,1,2,4})$ and $^{6}Li(d,x)^{7}Be$ reaction experimental data.**

- **Conflicting and unmatched integral cross section data in world literature.**

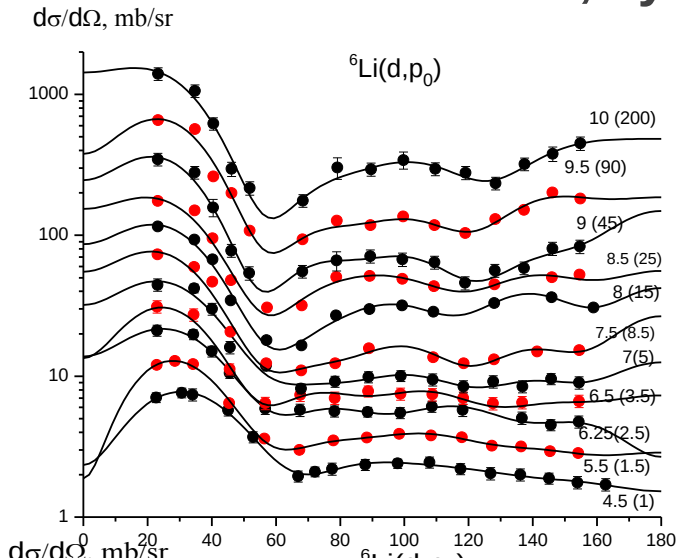
- **Appearance of the publication by Austin S.M. et al. (Phys. Rev. C. 2019. V. 99. Art. No 024320) with new evaluation of $^{6}Li(d,p_{1})$ and $^{6}Li(d,n_{1})$ reaction cross section.**

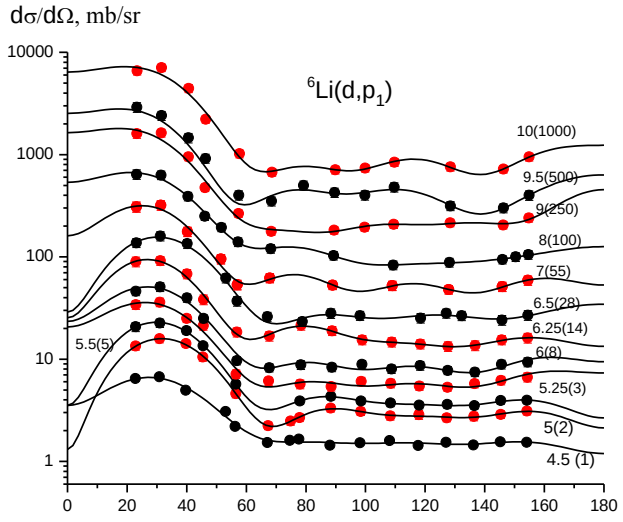
Goal

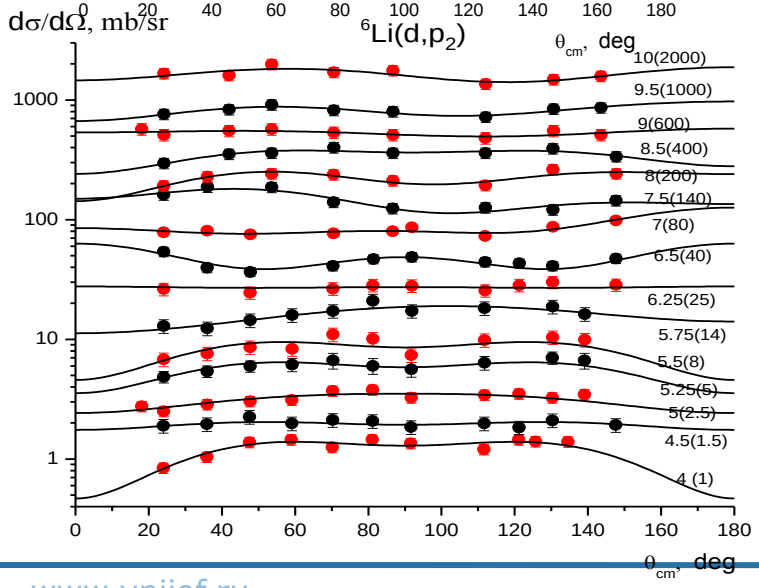
- **Obtaining of the $^{6}Li(d,p_0)^{7}Li$, $^{6}Li(d,p_{1,2,4})^{7}Li^*$, $^{6}Li(d,n_0)^{7}Be$, $^{6}Li(d,n_{1,2,4})^{7}Be^*$ and $^{6}Li(d,x)^{7}Be$ reactions evaluated integral cross section data.**

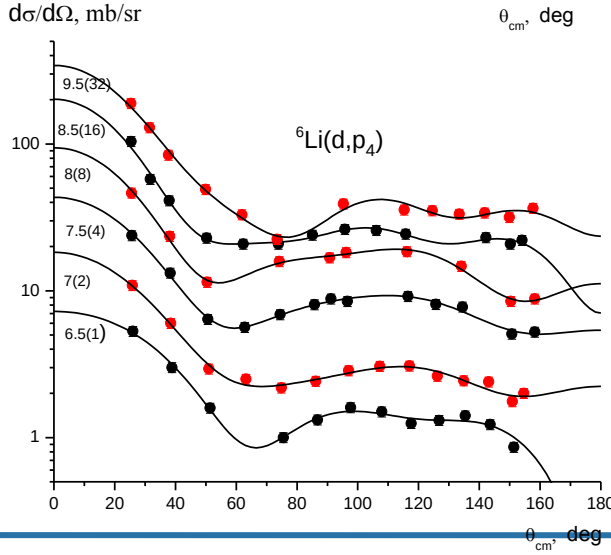
Data used in analysis (1/2)

Our data: scattering angle 20-160 degr, deuteron energy 4-10 MeV, random error 7-10%, systematic error 4%.









Circles - experimental points (multiplied by the relevant values in brackets), lines - Legendre polynomial fitting

(Experiment: Generalov L.N. et al. // Izv. RAS. 2020. V. 84. P. 1774.)

Data used in analysis (2/2)

- **Literature data**

Type	Scattering Angle, degr	E_d, MeV
dσ/dΩ (production of p or n or γ) (Legendre polynomial fitting for σ obtaining)	0-180	0.005-15
σ from the article	-	

- Data sets for (d,n_2) and (d,n_4) reactions are poor. So **data from (d,p_2) and (d,p_4) reactions** were used as cross section data **for the relevant mirror reactions (d,n_2) and (d,n_4).**

SaBa Data Base(1/5)

- The library of evaluated and experimental data on charged particles interactions with light nuclei developed at VNIIEF.
- 134 reaction channels; data types: integral and differential cross sections and nuclear reaction rates.
- No-model approach is used for obtaining of evaluated data.
- Evaluated function

$$f = S(E) + R(E)$$

Smooth part - spline

$$S(E) = \sum_{j=0}^{p} a_j (E - x_0)^j$$

Breit-Wigner resonances

$$R_l(E) = \sum_{i=0}^{n_l - 1} \frac{H_i (\Gamma_i / 2)^2}{(E - E_i)^2 + (\Gamma_i / 2)^2} + \delta_l \sum_{j=0}^{p_l} a_j (E - x_0)_j$$

resonance **background**

SaBa Data Base (2/5)

- **Astrophysical S-factor is used for evaluation**

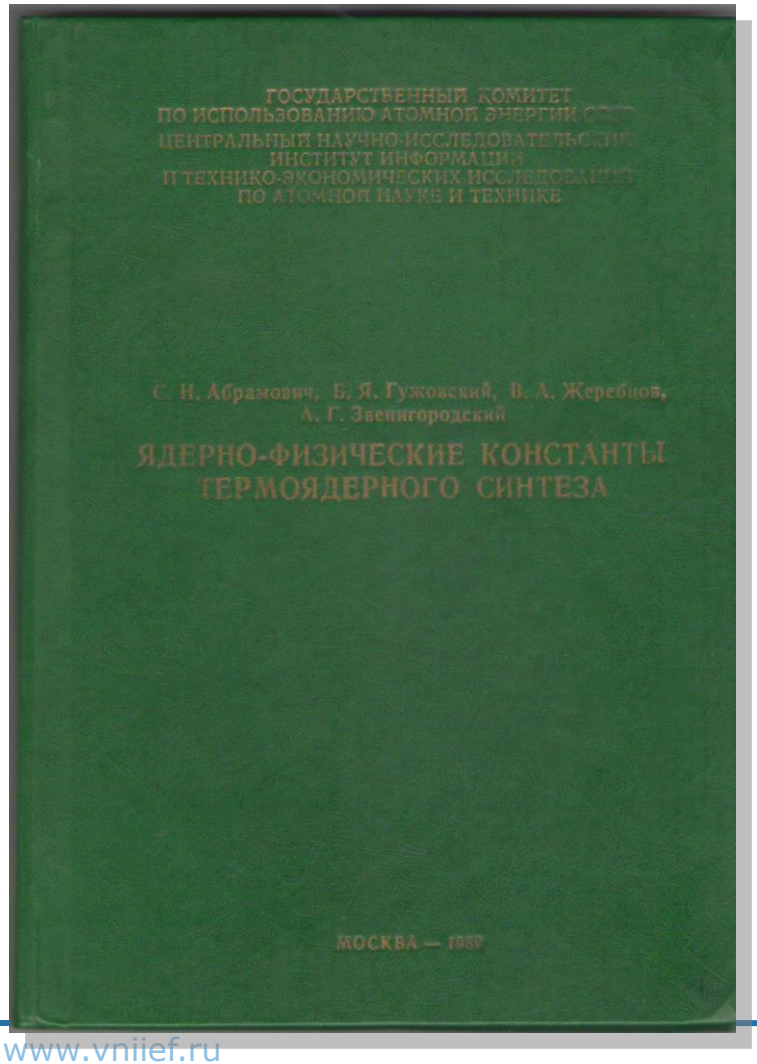
$$S(E_{cm}) = \sigma(E_{cm}) E_{cm} \exp\left(\sqrt{\frac{E_G}{E_{cm}}}\right) \quad \sqrt{E_G} = 0.98948 \; z_1 z_2 \sqrt{\frac{m_1 m_2}{m_1 + m_2}}$$

- **X^2 minimization for quality control of the evaluated curve**

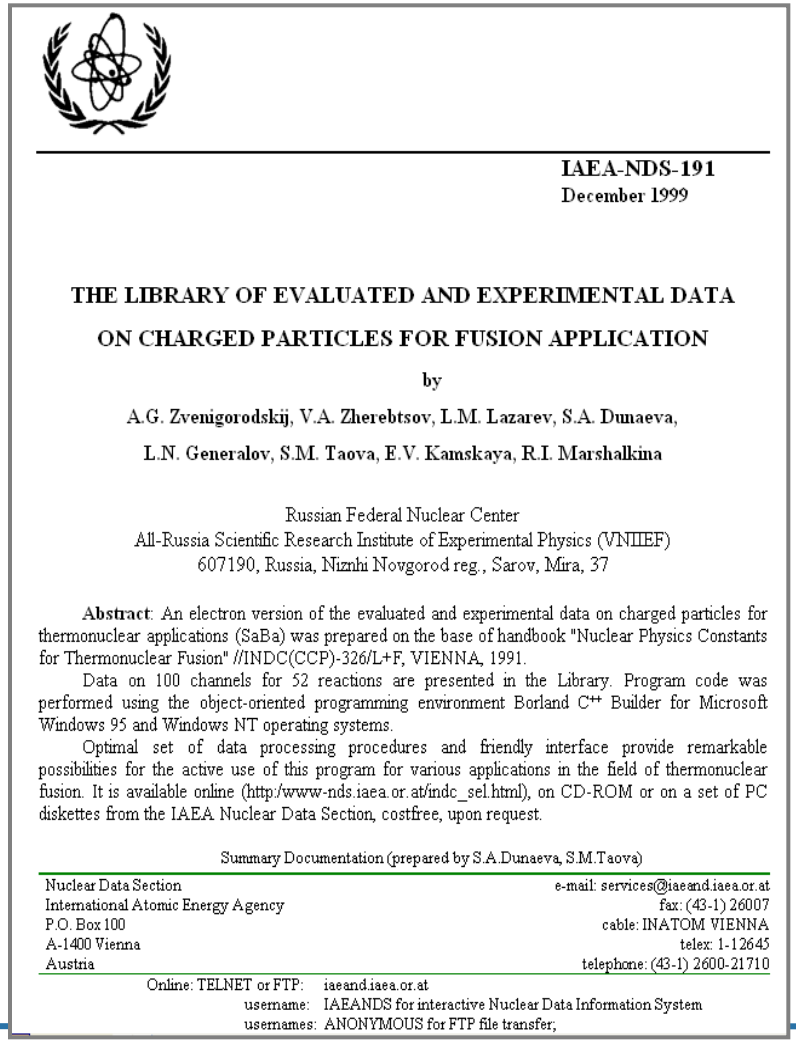
$$\chi^2 = \frac{\sum_{i=1}^{N_d} \left(\frac{S_i - f(E_i)}{\sigma_i} \right)^2}{N_d - N_p}$$

SaBa Data Base (3/5)

- First version, 1989



- IAEA report, 1999



IAEA-NDS-191
December 1999

THE LIBRARY OF EVALUATED AND EXPERIMENTAL DATA ON CHARGED PARTICLES FOR FUSION APPLICATION

by

A.G. Zvenigorodskij, V.A. Zherebtsov, L.M. Lazarev, S.A. Dunaeva, L.N. Generalov, S.M. Taova, E.V. Kamskaya, R.I. Marshalkina

Russian Federal Nuclear Center
All-Russia Scientific Research Institute of Experimental Physics (VNIIEF)
607190, Russia, Niznhi Novgorod reg., Sarov, Mira, 37

Abstract: An electron version of the evaluated and experimental data on charged particles for thermonuclear applications (SaBa) was prepared on the base of handbook "Nuclear Physics Constants for Thermonuclear Fusion" //INDC(CCP)-326/L+F, VIENNA, 1991.

Data on 100 channels for 52 reactions are presented in the Library. Program code was performed using the object-oriented programming environment Borland C++ Builder for Microsoft Windows 95 and Windows NT operating systems.

Optimal set of data processing procedures and friendly interface provide remarkable possibilities for the active use of this program for various applications in the field of thermonuclear fusion. It is available online (http:/www-nds.iaea.or.at/indc_sel.html), on CD-ROM or on a set of PC diskettes from the IAEA Nuclear Data Section, costfree, upon request.

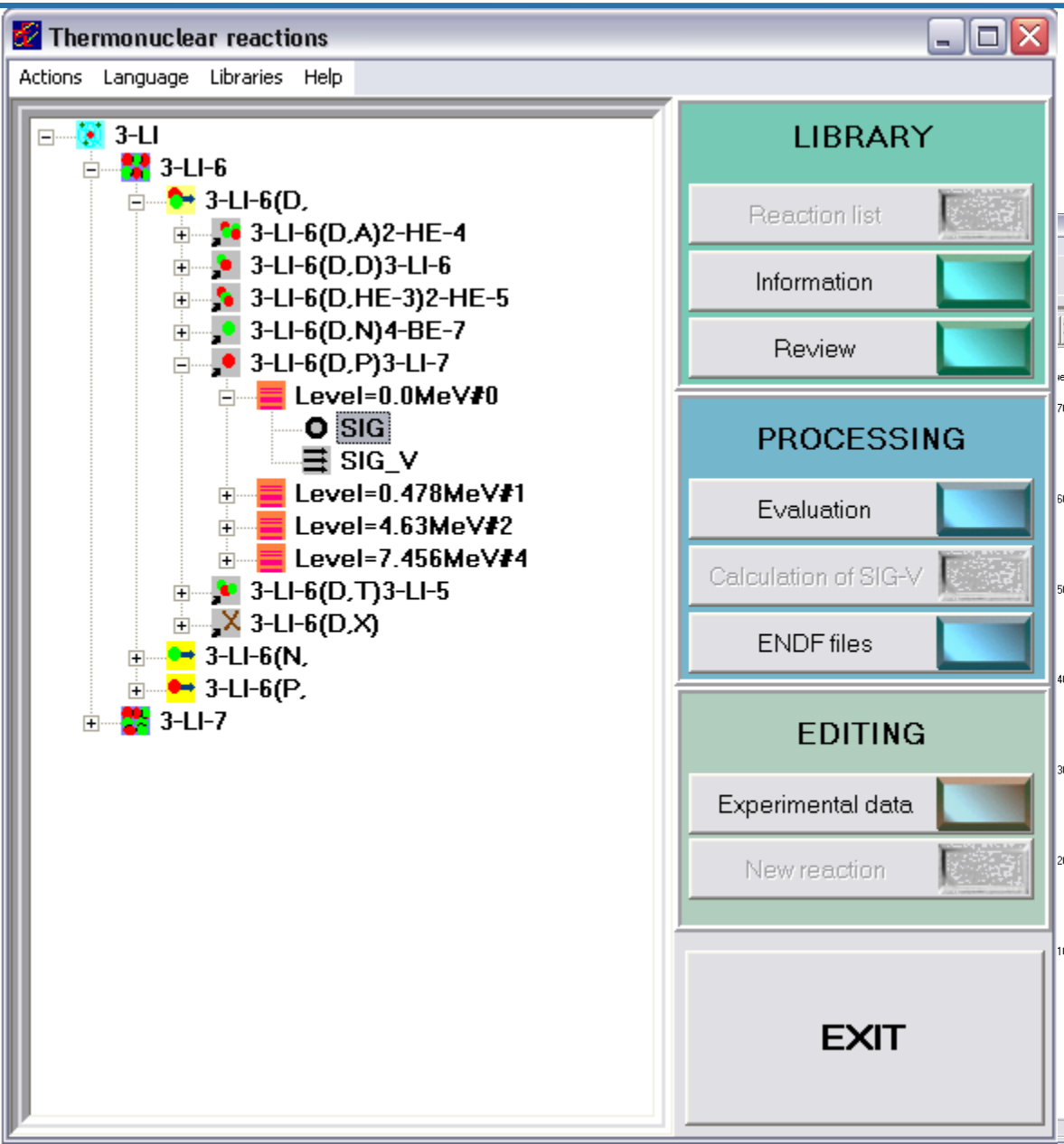
Summary Documentation (prepared by S.A.Dunaeva, S.M.Taova)

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

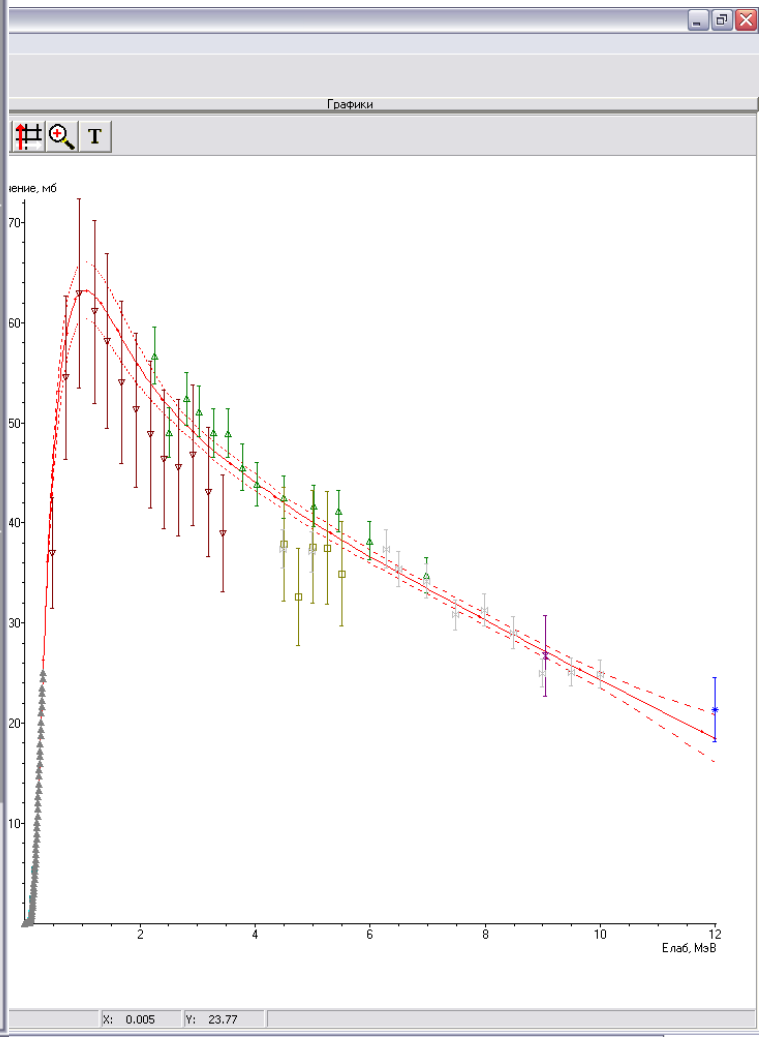
e-mail: services@iaeand.iaea.or.at
fax: (43-1) 26007
cable: INATOM VIENNA
telex: 1-12645
telephone: (43-1) 2600-21710

Online: TELNET or FTP: iaeand.iaea.or.at
username: IAEANDS for interactive Nuclear Data Information System
usernames: ANONYMOUS for FTP file transfer;

SaBa Data Base (4/5)



- Electron version, 2002



SaBa Data Base (5/5)

ГСССД

ГОСУДАРСТВЕННАЯ СЛУЖБА
СТАНДАРТНЫХ СПРАВОЧНЫХ ДАННЫХ (ГСССД)

Всероссийский научно-исследовательский центр стандартизации, информации и сертификации сырья, материалов и веществ (ВНИЦСМВ)

СВИДЕТЕЛЬСТВО

№ 460

Решением Всероссийского научно-исследовательского центра стандартизации, информации и сертификации сырья, материалов и веществ «22» апреля 2002г. (протокол № 2) данным

БИБЛИОТЕКА ОЦЕНЕННЫХ И ЭКСПЕРИМЕНТАЛЬНЫХ ДАННЫХ ПО РЕАКЦИЯМ НА ЗАРЯЖЕННЫХ ЧАСТИЦАХ ДЛЯ ПРИЛОЖЕНИЙ ТЕРМОЯДЕРНОГО
(наименование)

разработанным СИНТЕЗА
ЗВЕНИГОРОДСКИМ А.Г., ЖЕРЕБЦОВЫМ В.А., ЛАЗАРЕВЫМ Л.М.,
ДУНАЕВОЙ С.А., ГЕНЕРАЛОВЫМ Л.Н., ТАОВОЙ С.М., КАМСКОЙ Е.В.,
МАРШАЛКИНОЙ Р.И.
(фамилия, имя, отчество разработчика)

присвоена категория

РЕКОМЕНДУЕМЫЕ СПРАВОЧНЫЕ ДАННЫЕ (РСД)

Таблицы РСД зарегистрированы во Всероссийском научно-исследовательском центре стандартизации, информации и сертификации сырья, материалов и веществ
«22» апреля 2002 г.

под № ГСССД Р460 - 02

М.П.

Директор ВНИЦСМВ /А.Д. Козлов/
(подпись)

- State registration, recommended data,2002
- #460

Mirror reactions

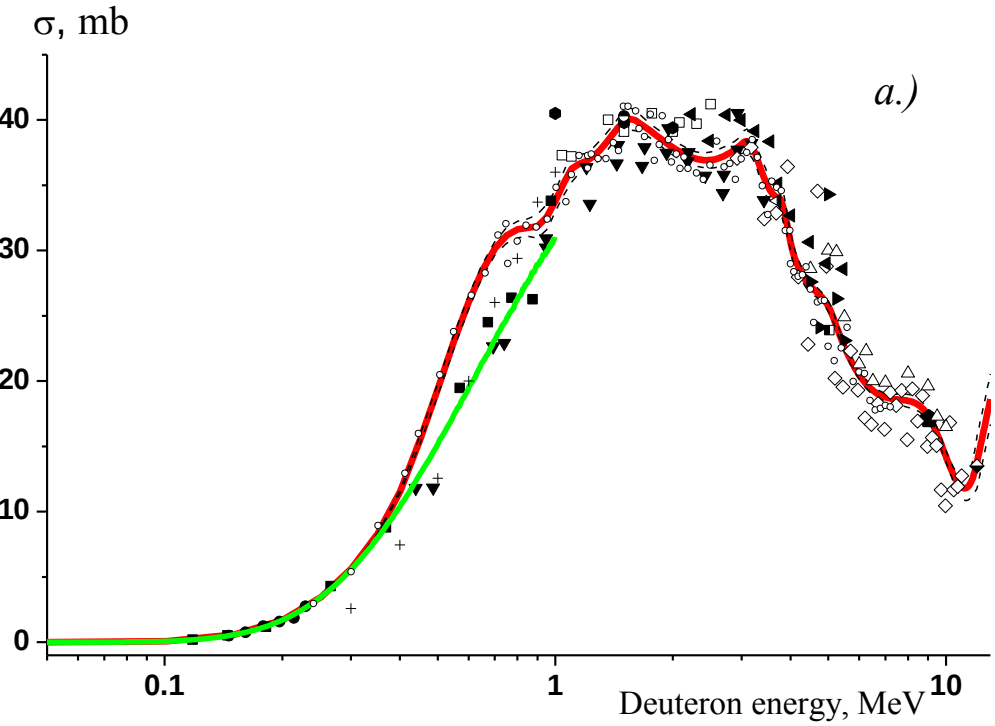
dp-реакции	*Q*, МэВ	E_{thr}, МэВ	*dn*-реакции	*Q*, МэВ	E_{thr}, МэВ
$^6Li+d \rightarrow {}^7Li_{g.s.}+p_0$	5.026		$^6Li+d \rightarrow {}^7Be_{g.s.}+n_0$	3.382	
$^6Li+d \rightarrow {}^7Li^*(0.478)+p_1$	4.548		$^6Li+d \rightarrow {}^7Be^*(0.429)+n_1$	2.953	
$^6Li+d \rightarrow {}^7Li^*(4.63)+p_2 \rightarrow {}^4He+t+p_2$	0.396		$^6Li+d \rightarrow {}^7Be^*(4.57)+n_2 \rightarrow {}^4He+he+n_2$	−1.188	1.584
$^6Li+d \rightarrow {}^7Li^*(6.68)+p_3 \rightarrow {}^4He+t+p_3$	−1.35	1.8	$^6Li+d \rightarrow {}^7Be^*(6.73)+n_3 \rightarrow {}^4He+he+n_3$	−3.35	4.47
$^6Li+d \rightarrow {}^7Li^*(7.46)+p_4 \rightarrow {}^4He+t+p_4 \rightarrow {}^6Li+n+p_4$	−1.564	2.085	$^6Li+d \rightarrow {}^7Be^*(7.21)+n_4 \rightarrow {}^4He+he+n_4 \rightarrow {}^6Li+p+n_4$	−3.83	5.11

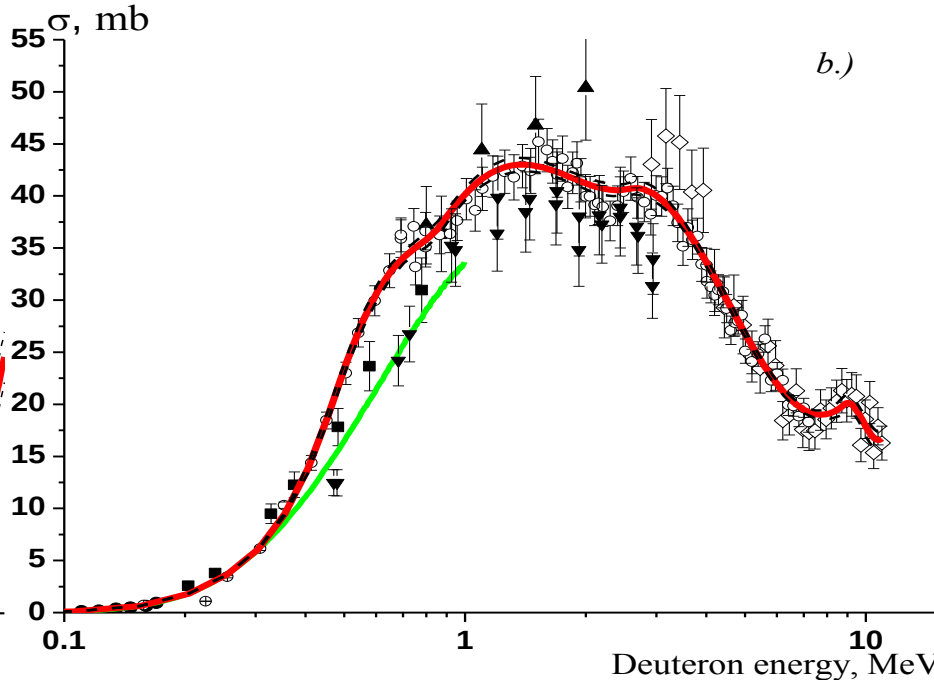
Evaluation features

- Our experimental results were used as reference ones.
- Each pair of mirror reactions was analyzed simultaneously: (d,p_0) and (d,n_0), (d,p_1) and (d,n_1), (d,p_2) and (d,n_2), (d,p_4) and (d,n_4). Evaluation of the data consisted of evaluation of the mirror reactions integral cross sections and its experimental ratios. Evaluation procedure was performed at iterative way.

Results 1/6

Evaluated integral cross sections of mirror reactions, red lines – present, green – K.Czerski,1997, direct+resonance





$^{6}Li(d,p_1)^{7}Li^*$

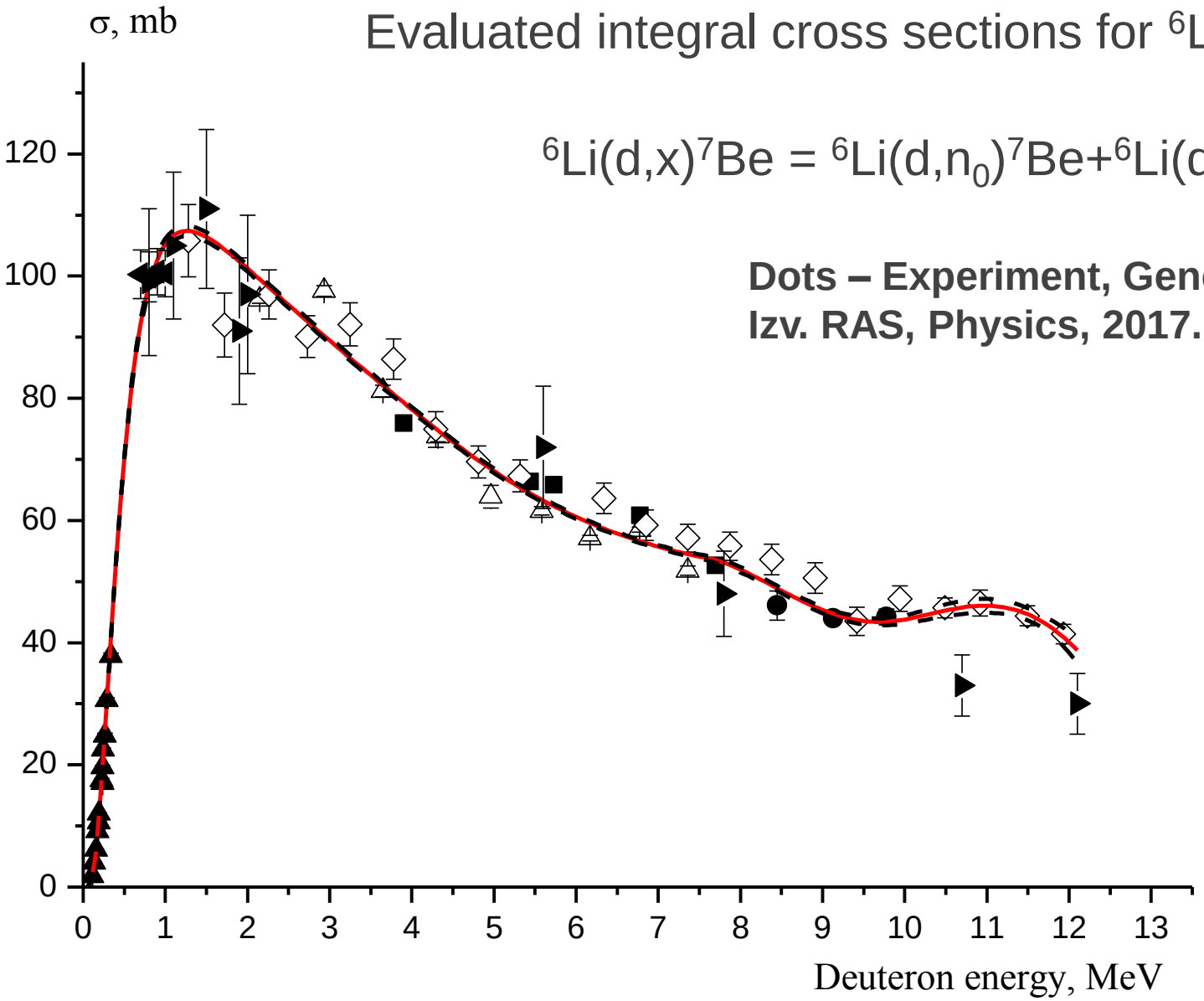
$^{6}Li(d,n_1)^{7}Be^*$

Results 2/6

Evaluated integral cross sections for $^{6}Li(d,x)^{7}Be$

$^{6}Li(d,x)^{7}Be = {}^{6}Li(d,n_0)^{7}Be + {}^{6}Li(d,n_1)^{7}Be$

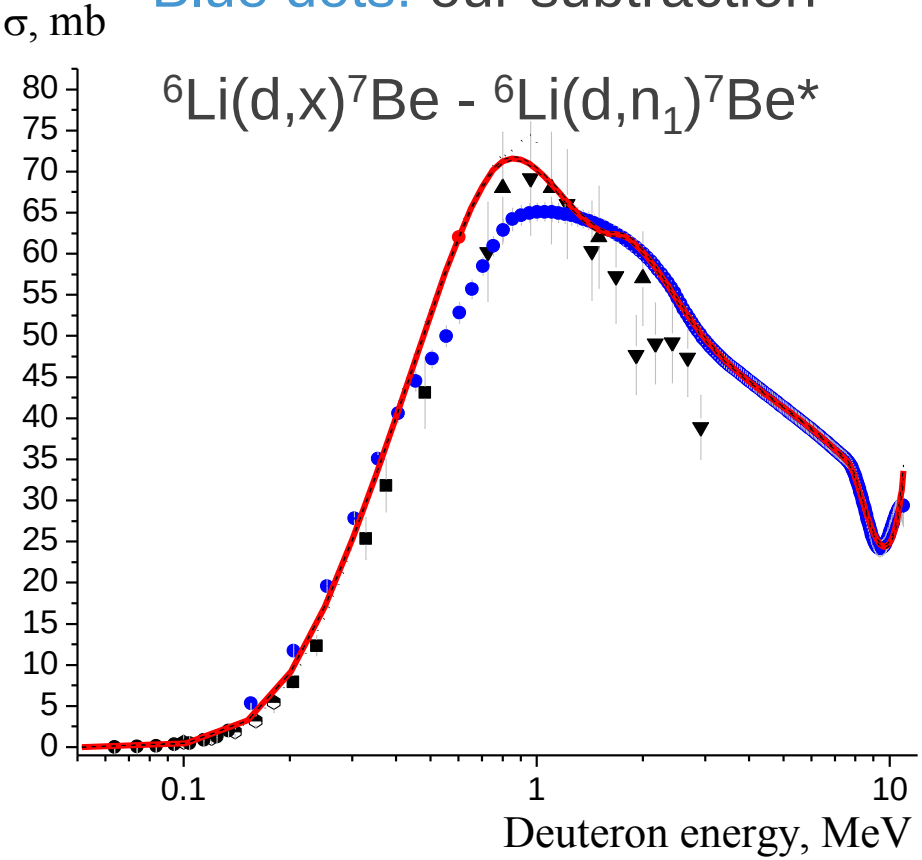
Dots – Experiment, Generalov et al, Izv. RAS, Physics, 2017. V.81. P. 717.

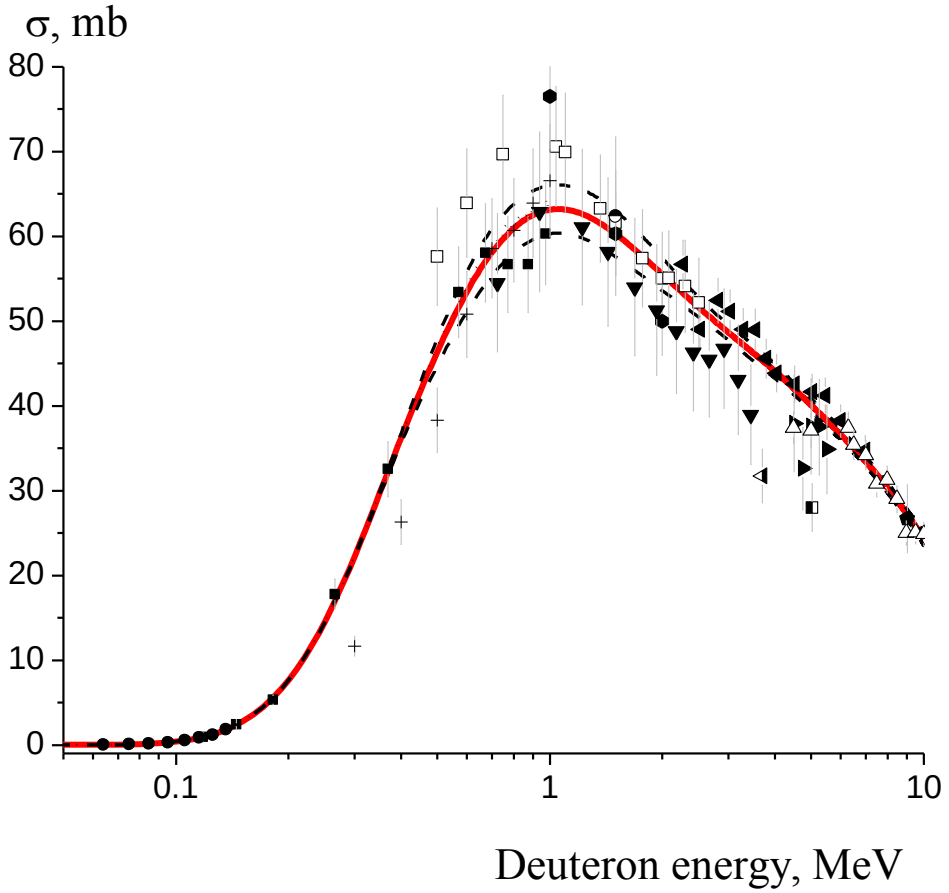


Results 3/6

Evaluated integral cross sections of mirror reactions, red lines - present

Blue dots: our subtraction



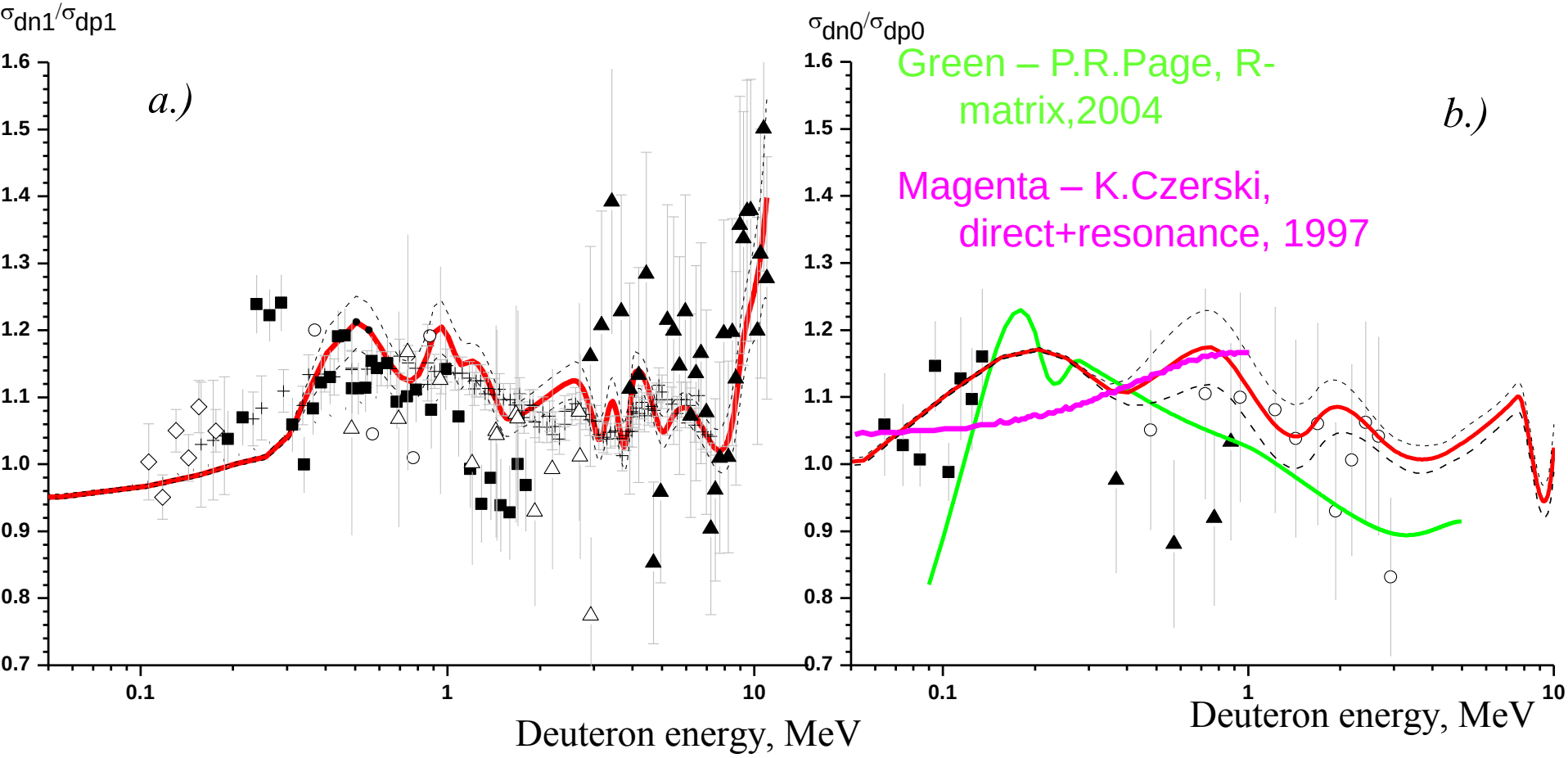


^{6}Li(d,n$_0$)^{7}Be

^{6}Li(d,p$_0$)^{7}Li

Results 4/6

Ratio of the mirror reactions integral cross sections, red lines - present



dn_1/dp_1

dn_0/dp_0

Data used in analysis (2/2)

- **Literature data**

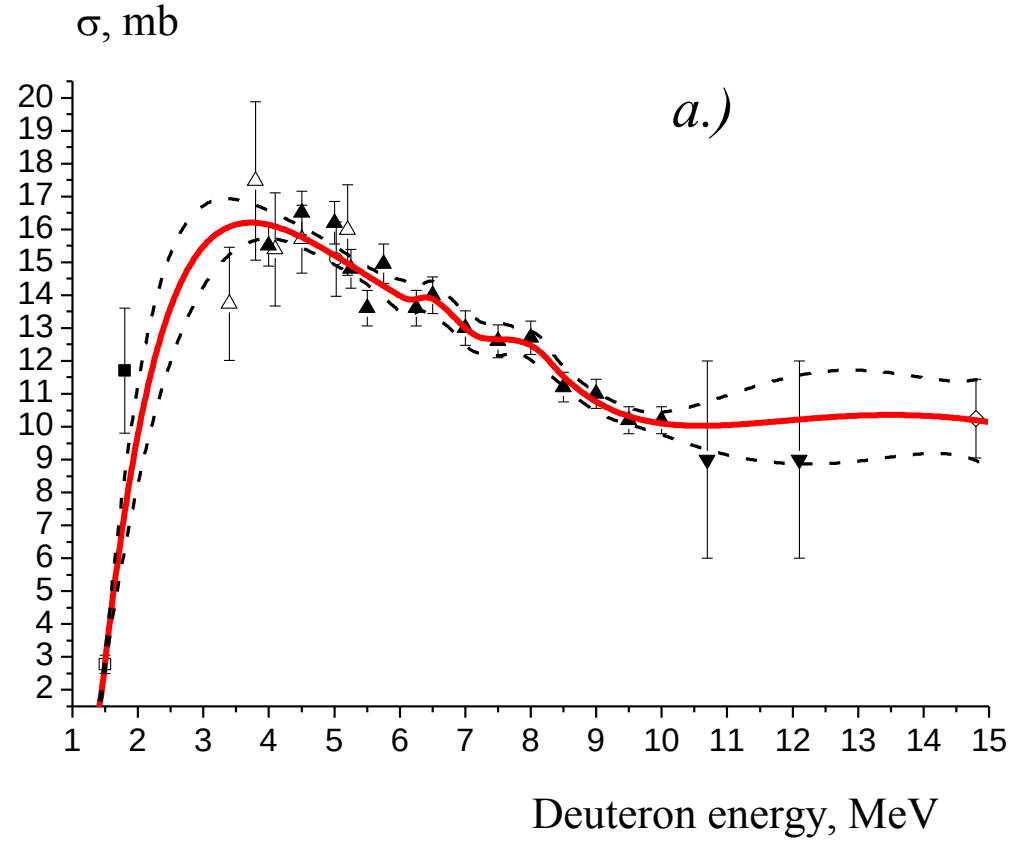
Type	Scattering Angle, degr	E_d, MeV
dσ/dΩ (production of p or n or γ) (Legendre polynomial fitting for σ obtaining)	0-180	0.005-15
σ from the article	-	

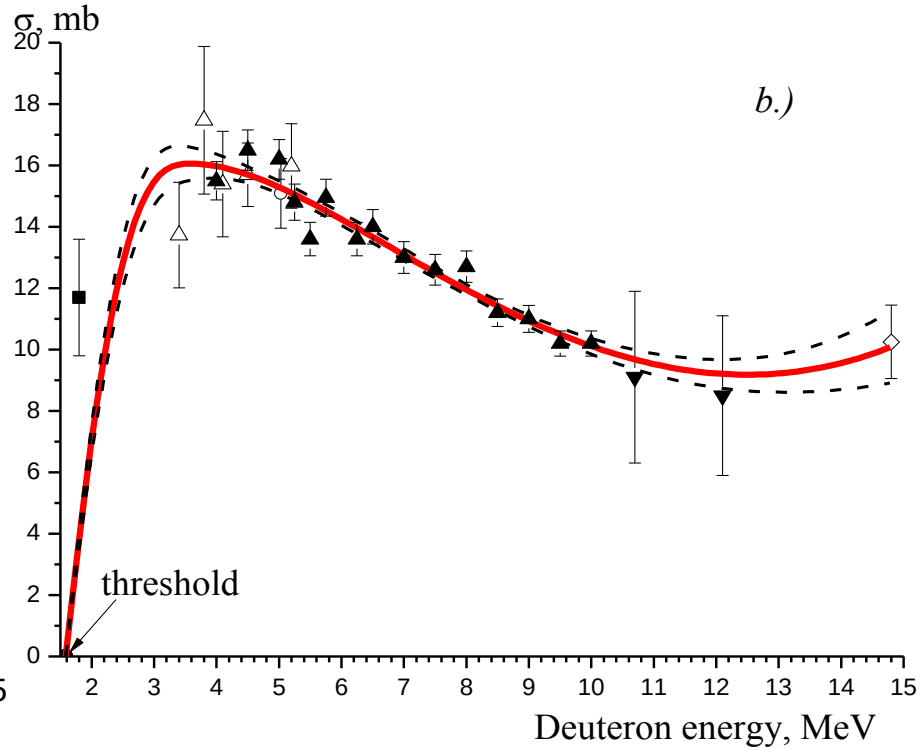
- Data sets for (d,n_2) and (d,n_4) reactions are poor. So **data from (d,p_2) and (d,p_4) reactions** were used as cross section data **for the relevant mirror (d,n_2) and (d,n_4) reactions.**

Results 5/6

РФЯЦ ВНИИЭФ

Evaluated integral cross sections of mirror reactions





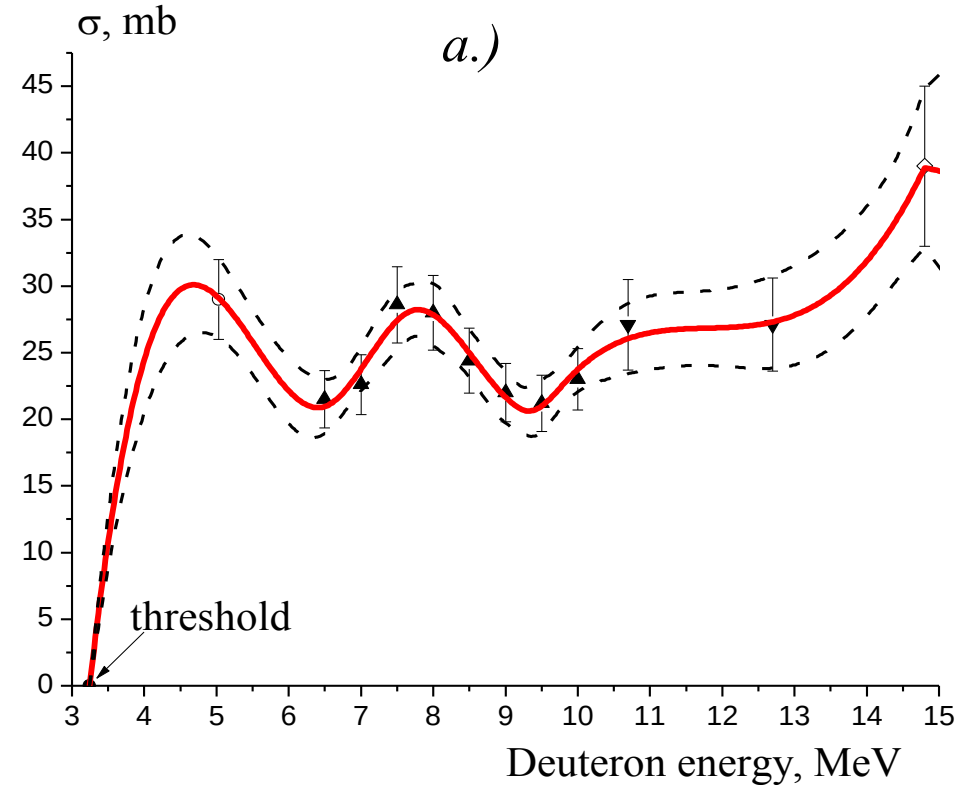
$^{6}Li(d,p_2)^{7}Li^*$

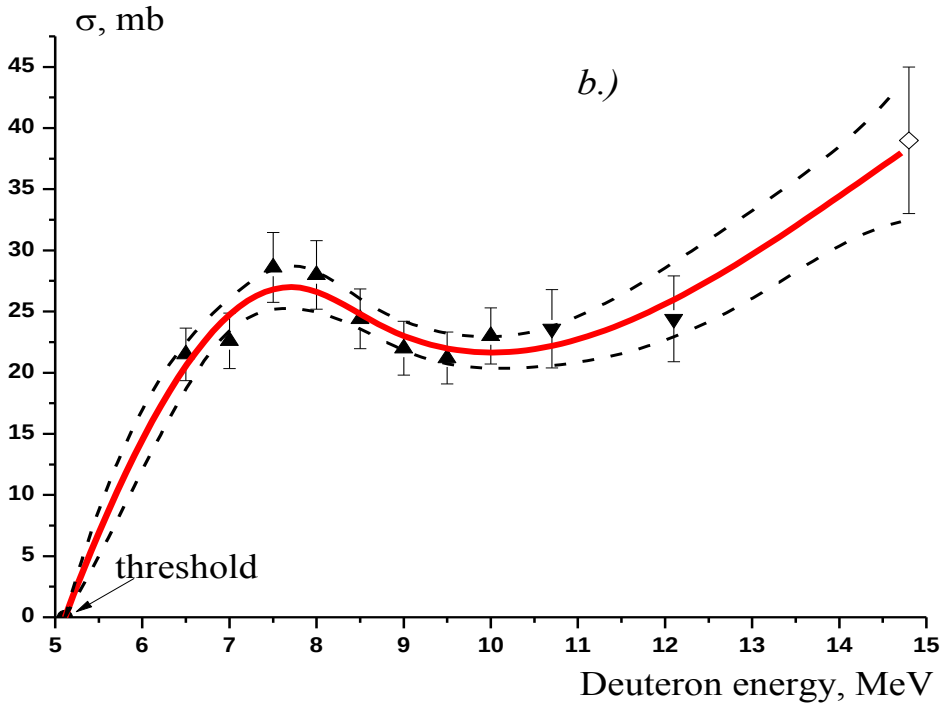
$^{6}Li(d,n_2)^{7}Be^*$

Results 6/6

РФЯЦ ВНИИЭФ

Evaluated integral cross sections of mirror reactions





$^{6}Li(d,p_4)^{7}Li^*$

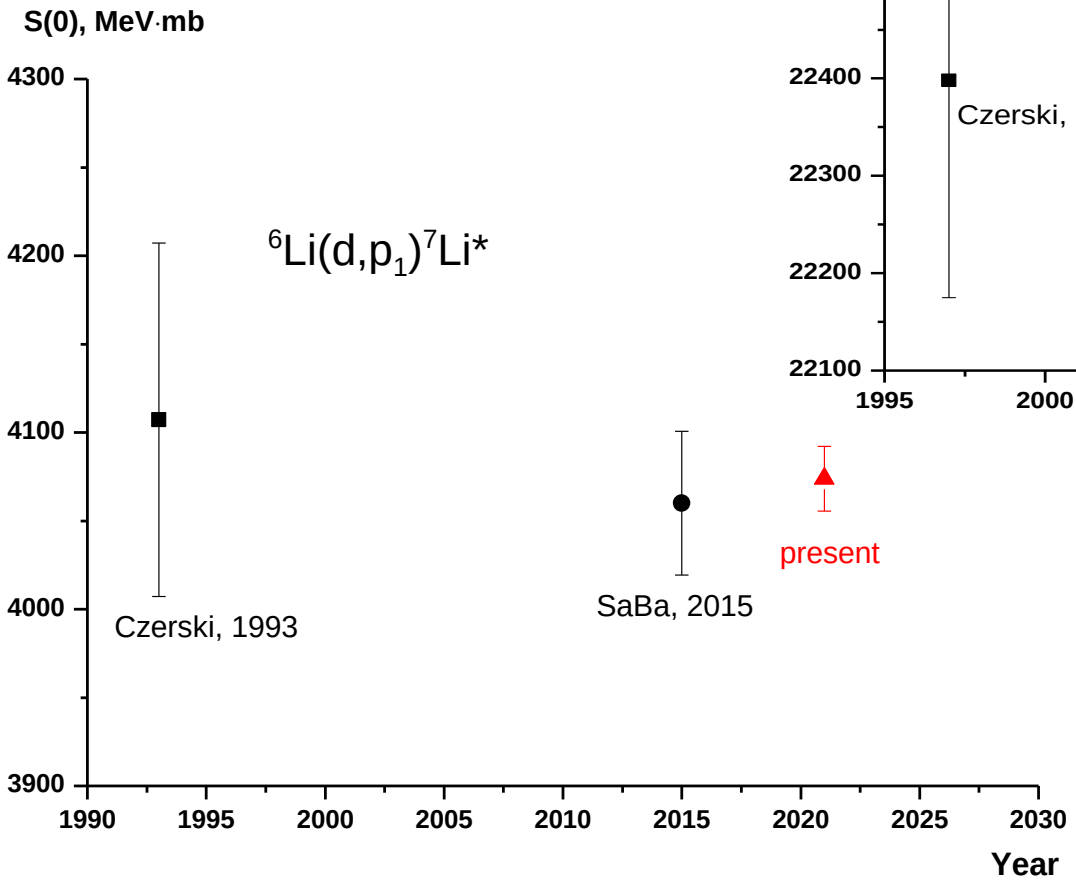
$^{6}Li(d,n_4)^{7}Be^*$

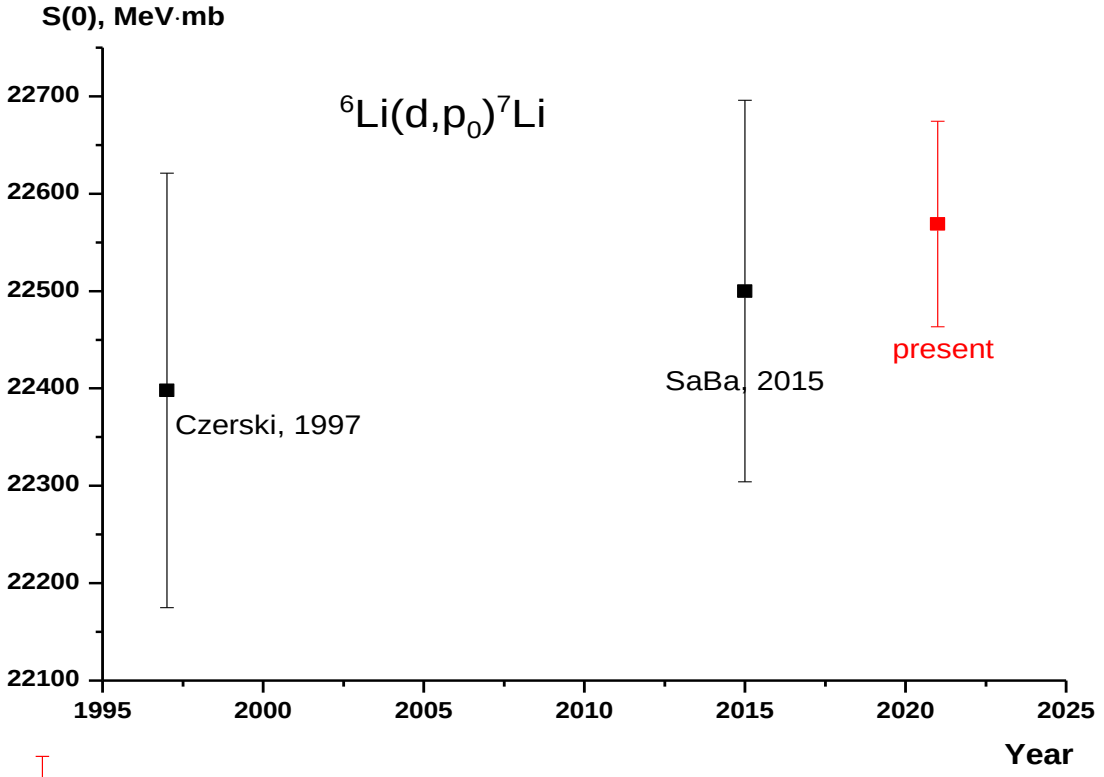
Spline coefficients (^{6}Li(d,p$_1$)^{7}Li*)

$$S(E) = C_0 + C_1(E - x_0) + C_2(E - x_0)^2 + C_3(E - x_0)^3$$

Энергия узла сплайна x_0, МэВ	Значения коэффициентов			
	C_0	C_1	C_2	C_3
$5.996 \cdot 10^{-3}$	$4.042 \cdot 10^{3}$	$-5.319 \cdot 10^{3}$	$-1.754 \cdot 10^{4}$	$6.781 \cdot 10^{4}$
$3.132 \cdot 10^{-1}$	$2.718 \cdot 10^{3}$	$3.098 \cdot 10^{3}$	$-2.916 \cdot 10^{4}$	$3.786 \cdot 10^{4}$
$6.568 \cdot 10^{-1}$	$1.875 \cdot 10^{3}$	$-3.535 \cdot 10^{3}$	$2.498 \cdot 10^{4}$	$-6.955 \cdot 10^{4}$
$8.532 \cdot 10^{-1}$	$1.618 \cdot 10^{3}$	$-1.768 \cdot 10^{3}$	$6.108 \cdot 10^{3}$	$-9.618 \cdot 10^{3}$
.....				
3.050	$7.310 \cdot 10^{2}$	$-3.179 \cdot 10^{2}$	$5.192 \cdot 10^{2}$	$-3.773 \cdot 10^{2}$
3.873	$6.109 \cdot 10^{2}$	$-2.293 \cdot 10^{2}$	$1.322 \cdot 10^{2}$	$-2.389 \cdot 10^{1}$
6.867	$4.684 \cdot 10^{2}$	$-8.009 \cdot 10^{1}$	$-6.362 \cdot 10^{1}$	$4.234 \cdot 10^{1}$
8.990	$4.168 \cdot 10^{2}$	$2.224 \cdot 10^{2}$	–	–

Astrophysical S-factor S(E=0), $^6Li(d,p_{0,1})^7Li$





CONCLUSION

- Evaluated integral cross sections of the $^{6}Li(d,p_0)^{7}Li$, $^{6}Li(d,p_{1,2,4})^{7}Li^*$, $^{6}Li(d,n_0)^{7}Be$, $^{6}Li(d,n_{1,2,4})^{7}Be^*$ and $^{6}Li(d,x)^{7}Be$ reactions were obtained.
- The ratio of the mirror reaction integral cross sections was obtained.

Thank you for your attention!