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New set of optical parameters for neutron scattering on ^{12}C nuclei

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TANGRA project

Project «**TANGRA**» (**TA**gged **N**eutron and **G**amma **RA**ys) at JINR-FLNP (Dubna) is aimed at studying nuclear reactions induced by fast neutrons. In the project's experimental setup the examined sample is irradiated by fast neutrons produced in a neutron generator. The main feature of the setup is usage of **tagged neutron method (TNM)**.

The essence of TNM is to register a characteristic particle, coming from the sample, in coincidence with the α-particle, accompanying neutron from the binary $d(t,\alpha)n$ reaction. TNM provides information about direction of generated neutron emission and enhance the effect/background ratio for registered signals.

Two types of particles are registered in the setups: γ-quanta and scattered neutrons. Angular distributions of γ-rays and partial cross sections of visible γ-transitions were mainly measured in previous TANGRA works [1-3].

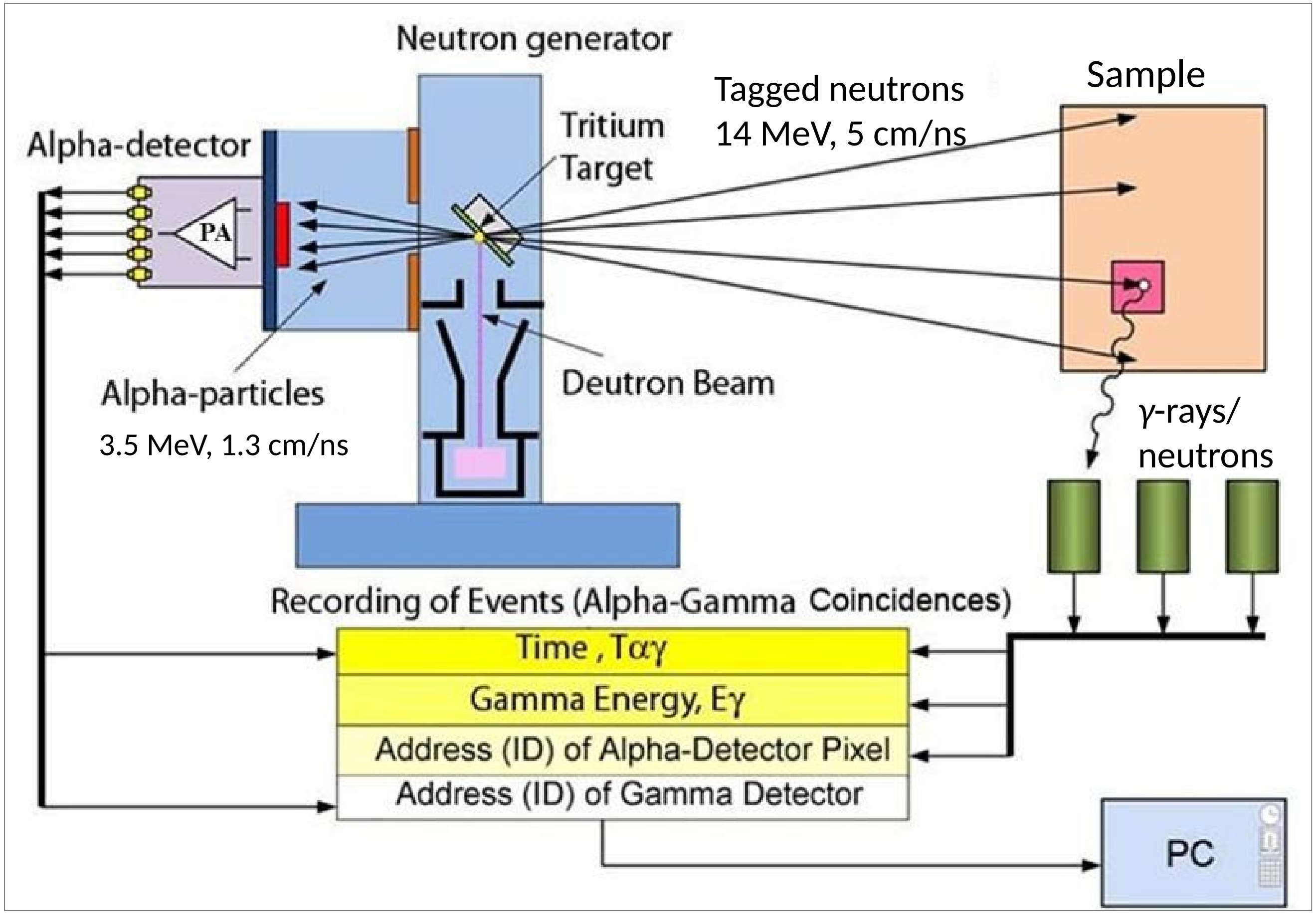


Fig. 1. TANGRA experimental setup general scheme.

1. N.A. Fedorov *et al.* Bull. Russ. Acad. Sci.: Phys. **84** (2020) 367
2. D.N. Grozdanov *et al.* Phys. At. Nucl. **83** (2020) 384
3. D.N. Grozdanov *et al.* Phys. At. Nucl. **81** (2018) 588

Experiment on angular distribution of scattered neutrons

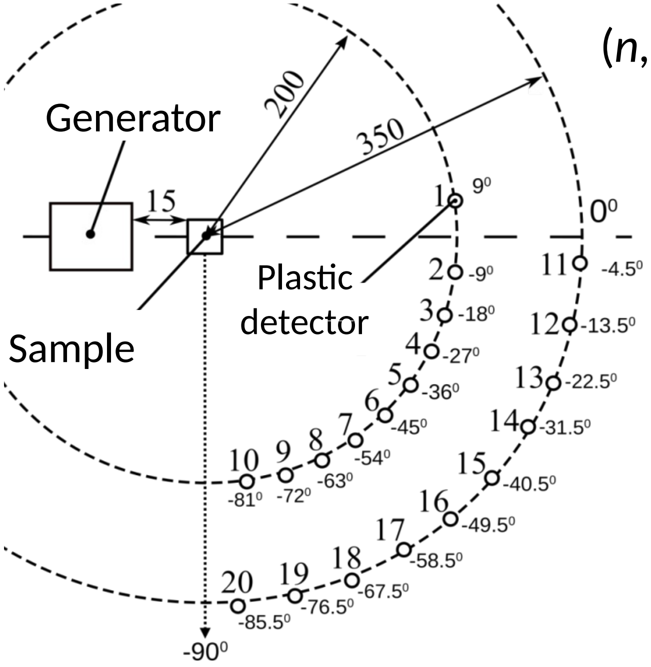


Fig. 2. Scheme of the TANGRA setup with plastic detectors for measuring angular distributions of the scattered neutrons. Distances and sizes are in cm. The neutron source is an ING-27 neutron generator, the registration system consists of 20 polyphenyltoluene detectors ($Z \approx 5.5$).

(n,n_0) and (n,n_1) reactions were considered: $n+{}^{12}C \to {}^{12}C+n$; $n+{}^{12}C \to {}^{12}C^{*}+n'$

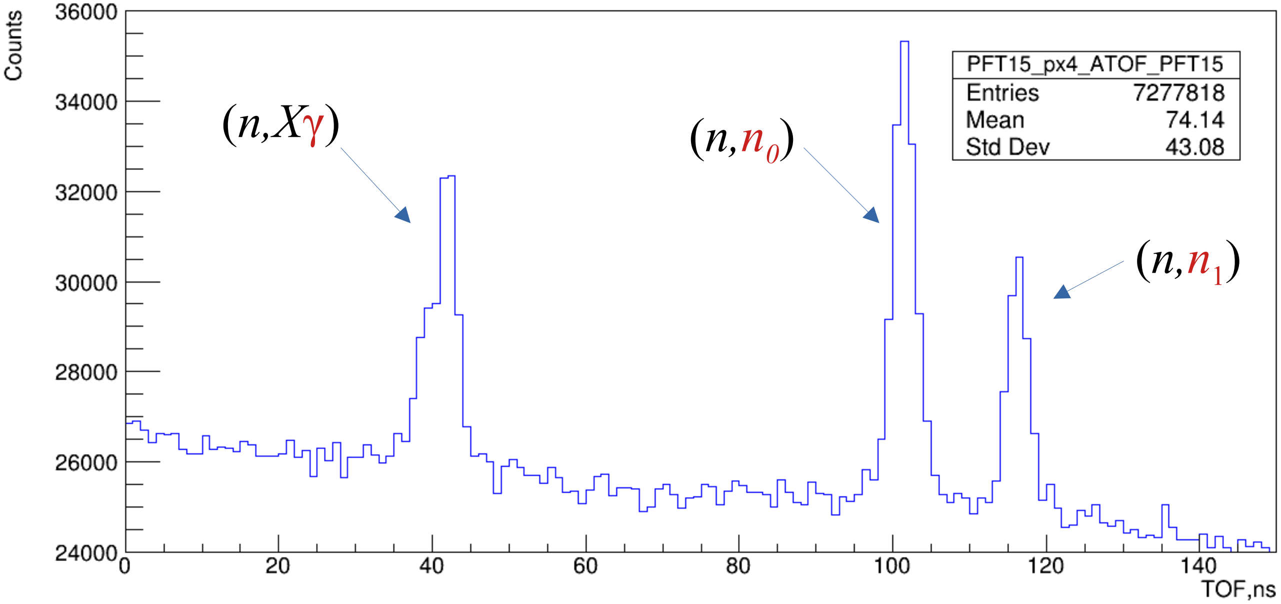


Fig. 3. Example of time-of-flight spectrum obtained in TANGRA experiment with carbon. Peaks are labelled with source reaction, registered particle is painted red.

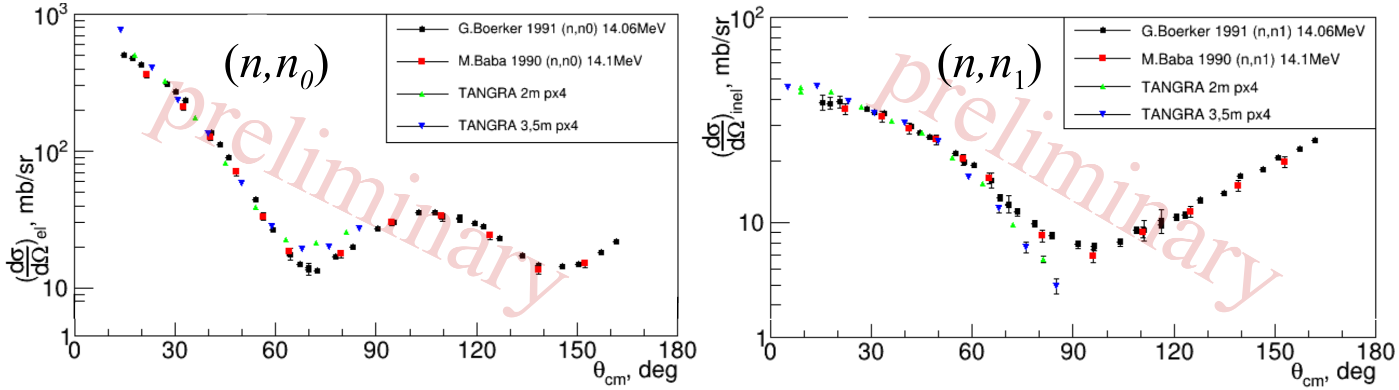


Fig. 4. Angular distributions for neutrons scattered on ${}^{12}C$ at an energy of 14.1 MeV. TANGRA preliminary results (blue and green) compared with other data[4,5] (black and red).

4. G.Boerker *at el*. Phys. Techn. Bundesanst., Neutronenphysik Reports, No.1 (1989) 1

5. M.Baba *et al*. Conf: JAERI-M Reports, No.90-025 (1990) 383

Object and instruments of the research

A carbon sample consists of carbon natural isotopes: **^{12}C (98.93%)**, ^{13}C (1.07 %). It is reasonable to describe only the most abundant isotope – ^{12}C.

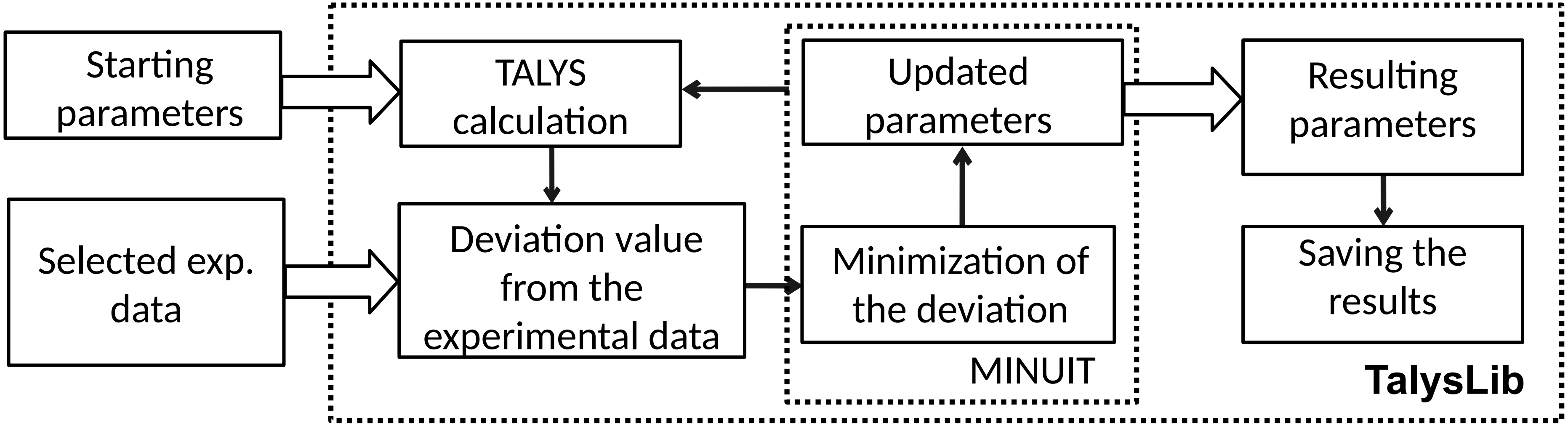
Optical model is widely used for neutron scattering description. To use the model it is necessary to obtain the parameters specific for considered nucleus and energy of the scattered neutron. Optical potential can be used in complimentary models, like coupled channels method for direct reactions treatment. To achieve more complete model description of the interaction, calculations using deformed nuclear optical potential with direct reactions and compound processes considered were carried out in nuclear reaction code TALYS 1.9.

In addition to the approach for describing direct processes, an important parameter for the model description of inelastic neutron scattering is the nuclear deformation. TALYS 1.9 default deformation parameters for the first excited state of ^{12}C are given in the table and compared with β_2 parameters specified in CDFE database and other sources.

	TALYS 1.9	CDFE database		Other sources
	β_2	β_2(B(E2)↑)	$\beta_2(Q_{mom})$	β_2 (from optical fit)
^{12}C	0.4	0.592 ± 0.036 [6]	-0.411 ± 0.226 [7]	-0.62 [8]

6. S.Raman *et al*. At. Data Nucl. Data Tables **78** (2001) 1
7. W.J.Vermeer *et al*. Phys.Lett. **122B** (1983) 23
8. Z.M Chen *et al.* J. Phys. G: Nucl. Part. Phys. **19** (1993) 877

Approximation procedure



Starting parameters

Selected exp. data

TALYS calculation

Deviation value from the experimental data

Updated parameters

Minimization of the deviation

MINUIT

Resulting parameters

Saving the results

TalysLib

Default (DWBA) → Our fit (CC rotational)

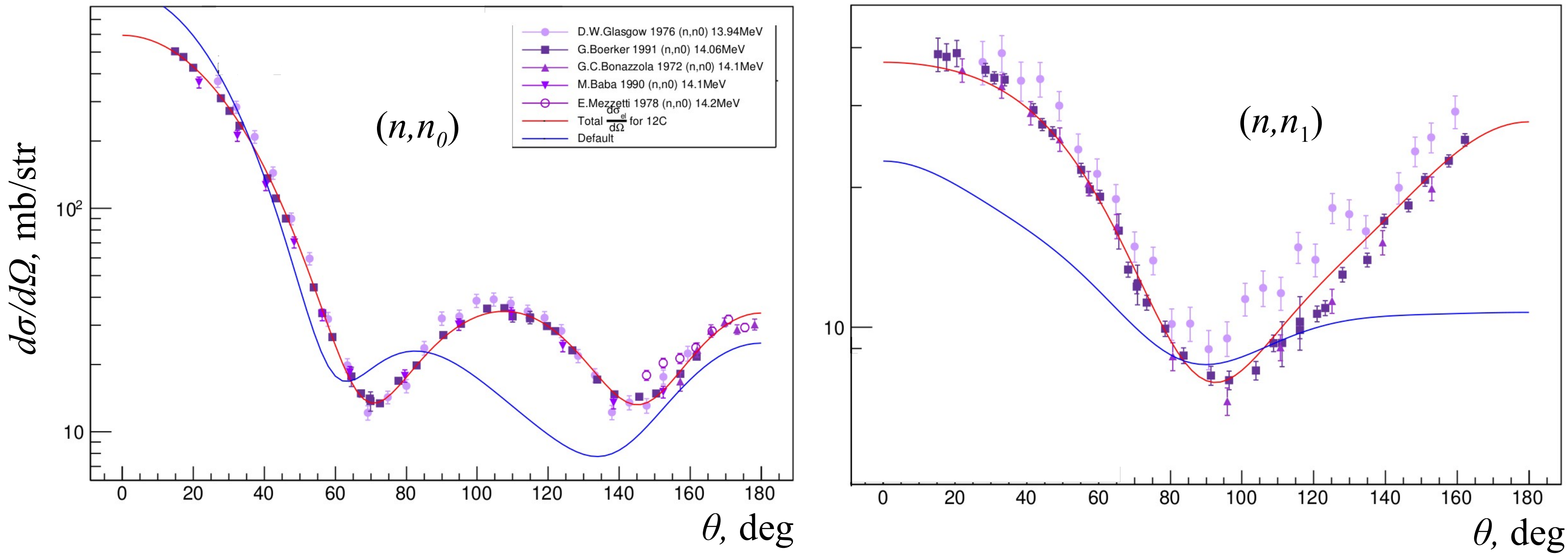


Fig.5. Differential cross section approximation in TalysLib for ^{12}C. Based on experimental data [4,5,9-11].

9. D.W. Glasgow *et al*. Nucl. Sci Eng. **61** (1976) 521. 10. G.C. Bonazzola *et al*. Lett. Nuovo Cimento **3** (1972) 99. 11. E. Mezzetti *et al*. Lett. Nuovo Cimento **22** (1978) 91.

Optical parameters for 14.1 MeV

Optical model parameters of TALYS 1.9 by default ($\chi^2/N = 111.8$):

	Approach	V_V MeV	W_V MeV	r_V fm	a_V fm	W_D MeV	r_D fm	a_D fm	V_{SO} MeV	W_{SO} MeV	r_{SO} fm	a_{SO} fm	β_2
^{12}C	DWBA	49.07	1.26	1.13	0.68	7.65	1.31	0.54	5.39	-0.07	0.90	0.59	0.40

Result optical model parameters gained from fit of experimental data ($\chi^2/N = 2.8$):

	Approach	V_V MeV	W_V MeV	r_V fm	a_V fm	W_D MeV	r_D fm	a_D fm	V_{SO} MeV	W_{SO} MeV	r_{SO} fm	a_{SO} fm	β_2
^{12}C	CC rot.	48.78	0.82	1.12	0.42	4.48	1.17	0.37	7.43	-1.92	1.20	0.60	-0.84

(*N* stands for number of experimental points used in the fit. The notations in the tables are the same as in the optical model parametrization of A.J. Koning and J.P. Delaroche [12].)

Comparison of integral cross sections of several processes taking place at 14.1 MeV:

	σ_{tot} mb	σ_{inl} mb	σ_{el} mb	$\sigma(n,n_1)$ mb	$\sigma(n,n_2)$ mb	$\sigma(n,n_3)$ mb	$\sigma_\gamma(2_1^+\rightarrow 0_{g.s.}^+)$ mb
Experiment	1290±100[13] 1430±100[14]	1,05	784±45[5]	203±12[5]	11±1[5]	63±4[5]	180±7[15] 168±20[16]
Default calc.	1572	341	866	142	19	68	202
After fit calc.	1264	293	826	211	8	22	237

12. A.J. Koning and J.P. Delaroche. Nucl.Phys.A **713** (2003) 231.
13. M.J.Rapp *et al.* Nucl. Sci Eng. **172** (2012) 268.
14. S.V.Artemov *et al.* Bull. Russ. Acad. Sci.: Phys. **84** (2020) 894.
15. I.Murata *et al.* Conf.on Nucl.Data For Sci.and Technol., Mito (1988) 275
16. V.C.Rogers *et al.* Nucl. Sci Eng. **58** (1975) 298

Conclusions

As a result of this work:

- Proof-of-concept experiment of neutron scattering on carbon carried out by TANGRA setup showed us possibility to measure angular distributions of scattered neutrons and even, with some improvements, differential cross sections of scattered neutrons.
- In the frame of symmetric rotator model of ^{12}C, new optical parameters and nucleus quadrupole deformation value, for ^{12}C interaction with 14.1 MeV neutrons, were obtained using our specially developed library, TalysLib.
- Low value of diffusiveness ($a_v = 0.42$ fm, $a_D = 0.37$ fm) and high quadrupole deformation value ($\beta_2 = - 0.84$) were found in the analysis.

Annex: Contributions of direct-interaction and compound nucleus mechanisms

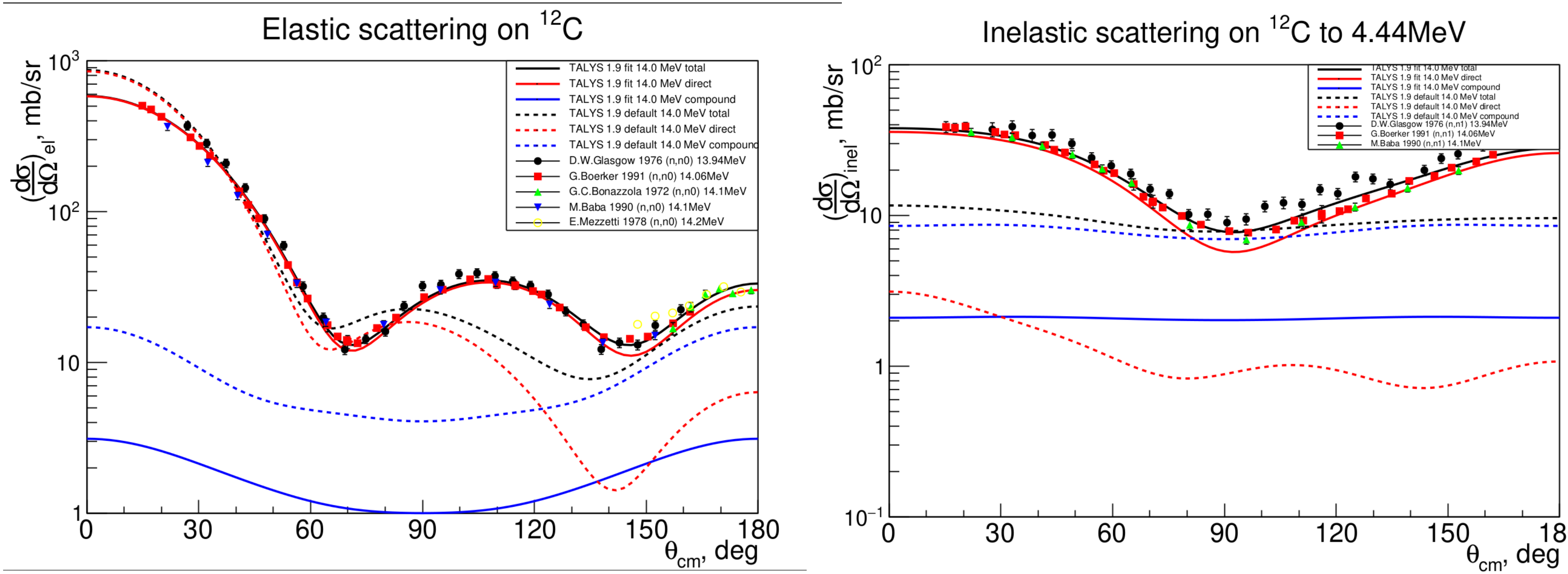


Fig.6. Differential cross sections for neutron scattered on ^{12}C. Red lines are direct reaction contributions, and blue lines are contributions of compound-nucleus mechanism. Solid lines correspond to the result of TalysLib fit, dashed lines are default TALYS 1.9 calculations. Compared with experimental data [4,5,9-11].

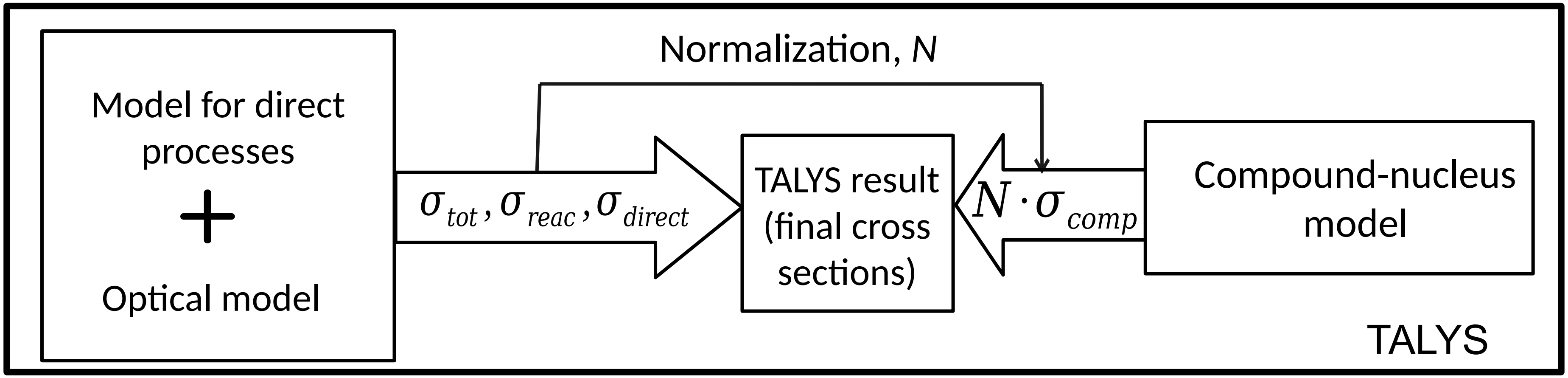
Annex: TALYS nuclear reaction code

TALYS is a code for nuclear reaction calculations. It covers an extensive range of projectile energies (1 keV – 200 MeV) and nuclei masses (A ≥ 12).

TALYS has implementations of several models for nuclear reaction description: for direct processes (DWBA, CC), compound-nucleus processes (Hauser-Feshbach models), nuclear level densities (Fermi-gas model and others).

TALYS 1.9 was used for calculation of:

- Partial γ-transitions cross sections
- Differential cross sections of elastic and inelastic neutron scattering



Model for direct processes

+

Optical model

Normalization, *N*

$\sigma_{tot}, \sigma_{reac}, \sigma_{direct}$

TALYS result (final cross sections)

$N \cdot \sigma_{comp}$

Compound-nucleus model

TALYS

Fig.7. Scheme of the complementary use of models in the TALYS 1.9 calculations.

Annex: Optical model potential

It is believed that the interaction between the neutron and the nucleus can be described by the complex potential.
Real part takes account of the refraction of particle wave on the nucleus border.
Imaginary part takes account of wave absorption as such, all of the nonelastic reactions.
Optical model cannot describe inelastic channels of nuclear reaction separately without some modifications.

The default optical model potentials used in TALYS are the local and global parametrisations of Koning and Delaroche [12]:

$$\mathcal{U}(r,E) = -\mathcal{V}_V(r,E) - i\mathcal{W}_V(r,E) - i\mathcal{W}_D(r,E) + \mathcal{V}_{SO}(r,E).\mathbf{l}.\sigma + i\mathcal{W}_{SO}(r,E).\mathbf{l}.\sigma$$

$$\begin{aligned}
\mathcal{V}_V(r,E) &= V_V(E) f(r,R_V,a_V), \\
\mathcal{W}_V(r,E) &= W_V(E) f(r,R_V,a_V), \\
\mathcal{W}_D(r,E) &= -4a_D W_D(E) \frac{d}{dr} f(r,R_D,a_D), \\
\mathcal{V}_{SO}(r,E) &= V_{SO}(E) \left(\frac{\hbar}{m_\pi c}\right)^2 \frac{1}{r}\frac{d}{dr} f(r,R_{SO},a_{SO}), \\
\mathcal{W}_{SO}(r,E) &= W_{SO}(E) \left(\frac{\hbar}{m_\pi c}\right)^2 \frac{1}{r}\frac{d}{dr} f(r,R_{SO},a_{SO}).
\end{aligned}$$

The form factor is a Woods-Saxon shape:

$$f(r,R_i,a_i) = \left(1 + \exp[(r-R_i)/a_i]\right)^{-1},$$

Annex: Models for direct processes

1. Distorted Wave Born Approximation (DWBA)

- Scattering and absorption are the main processes
- Any reaction channel does not have prevailing contribution to the total cross section.

2. Coupled channels method (CC)

- Full consideration of several selected reaction channels
- The influence of the discarded channels is taken into account through the optical potential of the nucleus

In case of spherical optical potential:

$$R_i = r_i A^{1/3}$$

In case of rotational model with static deformation:

$$R_i = r_i A^{1/3}\left[1 + \sum_{\lambda=2,4,\ldots} \beta_\lambda Y_\lambda^0(\Omega)\right],$$

In case of vibrational model with dynamic deformation:

$$R_i = r_i A^{1/3}\left[1 + \sum_{\lambda\mu} \alpha_{\lambda\mu} Y_\lambda^\mu(\Omega)\right],$$

Y — spherical harmonics, β_2 — quadrupole deformation of the nucleus