Measurements and usage of cross sections of various (n,*x*n) threshold reactions

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Abstract. Current trend in nuclear reactor physics is a transition from technologies using thermal neutrons to technologies utilizing fast neutrons. Unfortunately focus was put mainly on the thermal neutrons for a long time and lead to very good knowledge about this low energy region, but very scarce coverage of the high energy region. This means that there is a gap in the knowledge of excitation functions for higher energies. This gap spreads from 20 MeV up to 1 GeV and higher. This is exactly the energy region needed for description of advanced nuclear systems such as accelerator driven systems (ADS).

Our group from Nuclear Physics Institute (NPI) of the CAS is a member of an international collaboration Energy & Transmutation of Radioactive Waste (E&T RAW). This collaboration focuses on ADS for many years. In order to measure neutron field within ADS models it is necessary to know excitation functions of reactions used to monitor the neutron field. In many cases there are almost no experimental data for suitable reactions. Worse and quite common case is that there are no data at all. Therefore we are also focusing on measurements of these data in order to fill the databases as well as to allow further improvements of codes for nuclear data calculations.

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1 Introduction

Neutron field monitoring is crucial for many devices and systems such as spallation neutron sources, accelerator driven systems and other kinds of advanced nuclear systems. Since neutrons are electrically neutral hadrons it is difficult to detect them. The neutron spectroscopy is even more difficult. If it is not necessary to measure neutron flux on-line it is possible to take advantages of nuclear reactions and delayed measurements of a number of produced nuclei. One of possibilities is to utilize (n,xn) reactions and γ-spectroscopy methods.

Unfortunately experimental coverage and the knowledge of excitation functions are sufficient only for energies approximately up to 20 MeV. For higher energies the data are very scarce and as the consequence the parameters for the corresponding excitation functions are based rather on nuclear models than on experimental data. Our group from NPI focuses on cross section measurements of (n,xn) reactions on various materials. The purpose of using of various materials is to measure the neutron spectrum at some particular point based on the unfolding with help of the (n,xn) threshold reactions.

This article describes the procedure of calculation of cross section and possible problems which are necessary to be kept under the eye. Particularly it will be shown on the ^{197}Au(n,8n)^{190}Au reaction instance. Therefore its main purpose is to show the procedure, its peculiarities and the consequences arising from the insufficient amount of experimental data in higher energy region. Our group has long tradition in measurement of cross sections in various energy regions e.g. [1].

2 Cross section measurements

The road-plan of the measurement is quite straightforward. Going from the backwards the γ-spectroscopy methods are used to obtain the number of nuclei produced by the investigated reaction. In order to produce the nuclei it is necessary to irradiate samples with a viable neutron beam. The samples must be in form which allows good handling and measurement and must have mass which is optimized accordingly to the neutron source intensity. We are using thin metallic foils with dimensions in order of several squared centimeters and a mass of $\approx$0.5g.

2.1 Neutron source

For the cross sections measurements we take advantage of an opportunity to use a quasi-monoenergetic (QM) neutron source. In fact we are able to use two similar sources based on reaction ^{7}Li(p,n)^{7}Be. One is driven by the U-120M cyclotron at the NPI [2] and the other is driven by the Gustaf Werner Cyclotron at The Svedberg Laboratory (TSL) [3] of the Uppsala University. The ^{197}Au(n,8n)^{190}Au reaction was measured using the neutron source at TSL. The measurement was carried out within the EFNUDAT program.

2.2 γ-spectroscopy

After the irradiation and necessary security checks the samples are moved from irradiation housing to a spectroscopy laboratory. For the measurement a spectrometer based on HPGe detector is used. The obtained spectrum is then evaluated in a spectroscopy program. The evaluation consists of fitting the peaks which correspond to the γ-quanta emitted by the produced nuclei. The results from evaluation are in form of areas of the peaks which correspond to number of detected decays with respective errors originating from the fitting procedure. Once the areas are evaluated then the spectroscopy equation (1) [4] takes place. Various spectroscopic corrections are involved within discussed equation.

$$N_{yield} = \frac{S_{peak} \cdot C_{abs}(E)}{I_\gamma \cdot \varepsilon_p(E) \cdot COI(E) \cdot C_{area}} \frac{t_{real}}{t_{live}} \frac{e^{\lambda \cdot t_0}}{1 - e^{-\lambda \cdot t_{real}}} \frac{\lambda \cdot t_{irr}}{1 - e^{-\lambda \cdot t_{irr}}}. \tag{1}$$

The variables and parameters in the equation (1) are S_{peak} - peak area, $C_{abs}(E)$ - self absorption correction, I_γ - γ-quantum intensity, $\varepsilon_p(E)$ - peak efficiency, $COI(E)$ - coincidence correction coefficient, C_{area} - square emitter correction, t_{real} - real time, t_{live} - live time, t_0 - time between end of irradiation and start of the measurement, λ - decay constant, t_{irr} - time of the irradiation.

Once the yield is calculated it is possible to calculate the cross section for a particular reaction. Integral number of neutrons is necessary for the calculation. The calculation is described by a forthcoming equation (2)

$$\sigma = \frac{N_{yield} \cdot S \cdot A \cdot B_a}{N_n \cdot N_A \cdot m}. \tag{2}$$

The variables are S - sample area, A - atomic number, B_a - beam instability correction coefficient, N_n - number of neutrons, N_A - Avogadro's number and m - mass of the sample.

2.3 Background subtraction

Since the used neutron source is not monoenergetic the neutron spectrum consists of the QM peak and the lower energy continuum, it is necessary to perform a subtraction of the nuclei produced by the lower energy continuum. The correction can be quite significant. Its magnitude depends on the excitation function shape and reaction threshold energy. The neutron spectrum and one type of excitation functions is shown in figure 1(a). From this figure it is obvious how the low energy neutrons induce the investigated reaction.

In order to correct the number of produced nuclei N_{yield} we use a folding of neutron spectra and the excitation function. Particularly the ratio between the folding within the QM peak energy interval and the folding in the full neutron energy region. Since we have the spectra and excitation functions in form of bins, it is necessary to move from continuous integration into discrete summation. The procedure is expressed via equation (3).

$$C_{bgr} = \frac{\int\limits_{Peak} \sigma(E) \cdot N(E)\,dE}{\int\limits_{Spectrum} \sigma(E) \cdot N(E)\,dE} \longrightarrow C_{bgr} = \frac{\sum\limits_{i \in Peak} \sigma_i \cdot N_i}{\sum\limits_{i} \sigma_i \cdot N_i} \tag{3}$$

The variables stands for σ - excitation function and $N(E)$ for neutron spectrum. The number of nuclei produced by the QM peak is then

$$N_{yield}^{QM} = C_{bgr} \cdot N_{yield}. \tag{4}$$

3 Results and their development

Following the steps described earlier we have arrived to a result shown in figure 1(a). It is possible to see, that the agreement with TALYS 1.8 [5] calculation is excellent. The excitation function was obtained using default parameters with level density described using Constant Temperature Formula (CTF) and Back-shifted Fermi Gas Model (FGM). Since TALYS 1.8 provides a set of parameters based on the experimental data we have made another calculation using this parameterization called "'Best parameters'". The results together with the default model are shown in figure 1(b). Once again it is possible to see excellent agreement, which suggest strong model dependency. Figures 2(a) and (b) show the excitation functions calculated with TALYS 1.8 and different level density parameters used
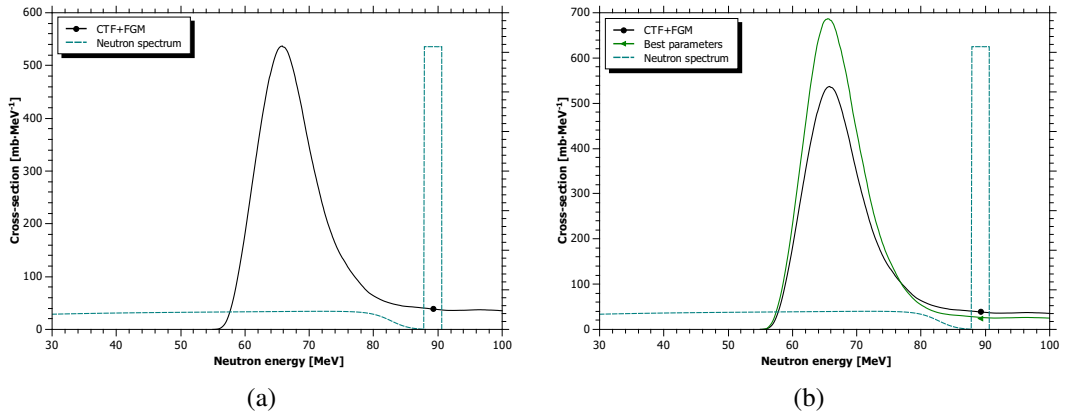
Figure 1. (a) Comparison between calculated excitation function with default parameters and experimental point; (b) Comparison of two parameterization of excitation function showing strong model dependency. Calculated excitation functions were used for background subtraction.

for the background subtraction procedure and corresponding results of cross section. It is possible to see, that the model dependence is more or less significant for all excitation functions.

First motivation for the previous calculations was to recalculate older results with the newest version of TALYS. Due to obtained results, a deeper study was conducted. Using script for fitting of the yields of two different isotopes with overlapping γ-lines the yields and cross sections for lower energies were obtained.
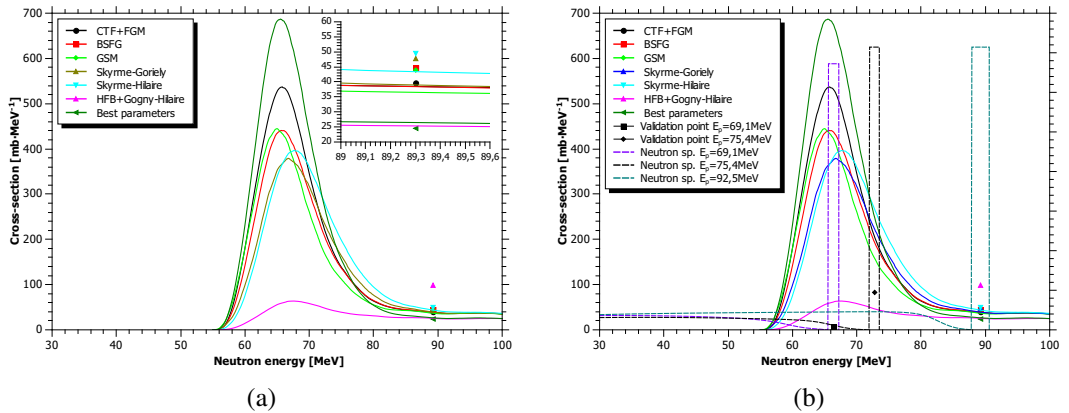
Figure 2. (a) Visualization of behavior of excitation functions with different models of level density and "best parameterization" and its effect on experimental values; (b) Introduction of additional experimental points in order to determine the most accurate excitation function.

Figure 2(b) shows that the excitation functions are highly overestimated and shifted to a lower energy. The calculations for the validation points were done without background subtraction procedure. However from the figure 2(b) it can be seen that those points would be influenced only slightly. This is proven in the next figure.

(a)   (b)
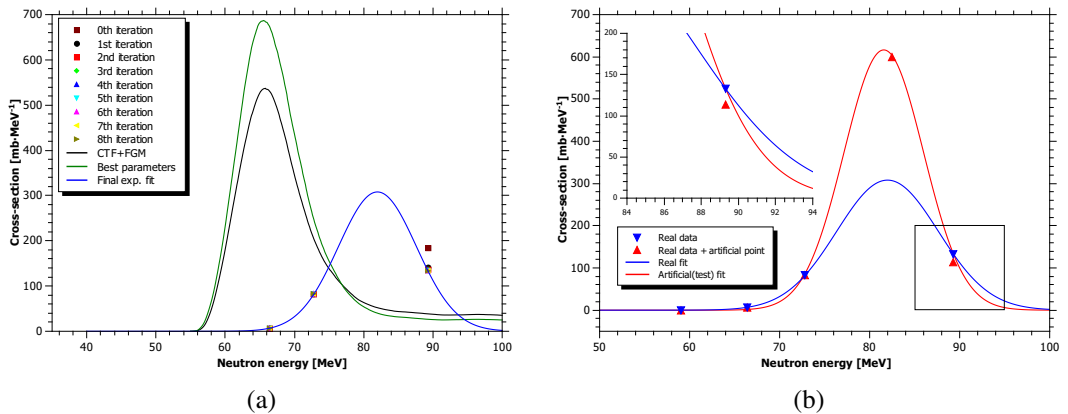
Figure 3. (a) Evolution of experimental points during self-consistent iteration of the excitation function; (b) Test of correctness of the excitation function maximum.

Figure 3(a) shows the iteration of the cross section points. It can be seen that first two points are almost without influence of the low energy neutrons. The third point has dropped after first step and then the changes were only minimal. The iteration was stopped when the relative changes were lower than 0.01%. Since there are no experimental data for the maximum of the fitted peak an artificial point was introduced into data-set to increase the maximum to similar value as the calculated excitation function. Figure 3(b) shows that the excitation function with the artificial point is overestimated. It is propagating as undershooting of the fitted excitation function if it is taken as the parameter for the background subtraction procedure. We can see no such undershooting for the excitation function without the artificial point.

4 Conclusion

We have seen that the calculated excitation functions and the corresponding cross sections calculated with their help do not have to be accurate even if there is good agreement between the calculation and the experiment. Furthermore it has shown up that the excitation function can be even shifted in energy. Our fit of the excitation function is performed with Gaussian as the fitted function. There is no reason to doubt that the calculated shape is completely wrong and the Gaussian agrees with this shape very well in the peak region. The disagreement in shape has only negligible influence on the results. Since we have no data in the tail region for higher energies we can use the Gaussian for the iterative background subtraction. The data are still in preliminary phase and that is the reason why there are no numerical data or the error bars. However there is not going to be any significant change of the outcome with the finalization.

Acknowledgments

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