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Study of pre-equilibrium contributions in proton spectra of ^{59}Co(n,xp) reaction using TALYS-1.9

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In the present study we have calculated the proton spectra of ^{59}Co(n,xp) using TALYS-1.9. TALYS uses all major reaction mechanisms like compound, pre-equilibrium and direct reactions. The contribution from compound nuclear reaction is calculated using optical model calculations. For pre-equilibrium contributions we have used two particle exciton model. The results from the present work suggests the presence of significant pre-equilibrium emission components in the ^{59}Co(n,xp) system within the range of incident projectile energies from 37.5 to 62.7 MeV.

Keywords: Pre-equilibrium reaction mechanisms, Exciton model, TALYS-1.9.

1 Introduction

There are many ways in which incident particle interacts with the target nucleus. The most common mechanisms of nuclear reaction are: direct, compound, and pre-equilibrium reactions. These three-processes are characterized according to their time scales and the number of intra-nuclear collisions occurs before emission. The pre-equilibrium reaction mechanism is one of the most challenging problems in nuclear theory. The pre-equilibrium reaction mechanism can be explained by using semi-classical exciton model. The primary equation of the exciton model is a time dependent master equation, which represents the probability of transition from one particle-hole state to another particle-hole state. If we integrate this equation over time, then we get the energy averaged emission spectrum. In this theory particle and hole are considered as excitons. The collision probability of particle-hole is calculated by the Fermi's golden rule of time dependent perturbation theory. $\lambda(n \rightarrow n') = 2\pi \langle M^2 \rangle \frac{\omega_f}{h}$, where $\langle M^2 \rangle$ is the free parameter, namely the average matrix element of the residual two-body interaction occurring in the transition rates between two exciton states and ω_f is the density of final state. With the proper parameterization of this matrix element, the predictive power of this model is found to be very convincing.

We have adjusted the value of average squared matrix element M^2 in TALYS to produce proton spectra for the ^{59}Co(n,xp) reaction at incident beam energy of 37.5, 41.0, 45.0, 49.0, 53.5 and 62.7 MeV. Since pre-equilibrium emission increases with increase in the incident energy[1,2]. This particular set of beam energies will help in studying the effect of incident beam energies on pre-equilibrium contribution. The calculated results are compared with the available experimental data from EXFOR[3,4].

EXFOR is the EXchange-FORmat for the transmissions of experimental nuclear reaction data between national and international nuclear data centers for the benefit of nuclear data users in all the countries. This is the library and format for the collection, storage, exchange, and retrieval of experimental nuclear reaction data. The library is the product of a worldwide co-operation, namely the international network of Nuclear Reaction Data Centres (NRDC) which is coordinated by the IAEAData Section (NDS)[5].

2 TALYS-1.9 Code

The TALYS-1.9 is a Fortran based theoretical nuclear reaction model code and is used for calculating various physical observables related to nuclear reaction[6,7]. In TALYS we can use neutrons, gamma-rays, protons, tritons, and alpha particles as projectiles in the 1 keV – 200 MeV energy range. The code provides the effect of level density parameters, compound, pre-equilibrium and direct reaction mechanism as a function of incident particle energy. TALYS can serve basically two purposes. First one as

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Nuclear Physics Tool, which is used for the analysis of nuclear reaction experiments. The comparison of experiments and theory sheds light on the fundamental interactions between particles and nuclei which in turn helps us to constrain our models. Second one as Nuclear Data Tool. TALYS can generate nuclear data for all open reaction channels, on a user-defined energy and angle range.

The main purpose of TALYS is to provide a complete set of answers for the nuclear reactions, all open channels and associated cross sections, spectra and angular distributions[8]. The following data can be calculated by TALYS:

i Total, elastic and reaction cross sections.
ii Non-elastic cross section per discrete state.
iii Elastic and non-elastic angular distribution.
iv Fission cross sections and fission yields.
v Discrete and continuum gamma-ray production cross sections.
vi Total particle-production cross sections, e.g., (n,xn).
vii Single- and double-differential particle spectra.

3 Exciton Model

The pre-equilibrium differential cross-section for the emission of particle k with energy E_K can be expressed as:

$$\frac{d\sigma_K^{PE}}{dE_K} = \sigma^{CF} \sum_{(P_\pi = P_\pi^0)}^{P_\pi^{max}} \sum_{(P_\nu = P_\nu^0)}^{p_\nu^{max}} W_k(p_\pi, h_\pi, p_\nu, h_\nu, E_k)\ \tau\,(p_\pi, h_\pi, p_\nu, h_\nu)\ P(p_\pi, h_\pi, p_\nu, h_\nu) \quad ...(1)$$

$p_\pi(p_\nu)$is proton(neutron) particle number, $h_\pi(h_\nu)$ is proton(neutron) hole number, $n_\pi = p_\pi + h_\pi$ is proton exciton number and $n_\nu = p_\nu + h_\nu$ is neutron exciton number. Then total exciton number will be $n = n_\pi + n_\nu$.

In the above equation, σ^{CF} is composite nucleus formation cross section, W_k is emission rate, τ is life time of exciton state (p_π, h_π, p_ν, h_ν), P represents the pre-equilibrium population that has survived emission from the previous states and now passes through the (p_π, h_π, p_ν, h_ν) configuration.

The lifetime τ of exciton state is defined as the inverse sum of the total emission rates and internal transition rates:

$$\tau\,(p_\pi, h_\pi, p_\nu, h_\nu) = [\,\lambda_\pi^+(p_\pi, h_\pi, p_\nu, h_\nu) + \lambda_\nu^+(p_\pi, h_\pi, p_\nu, h_\nu) + \lambda_{\pi\nu}^0(p_\pi, h_\pi, p_\nu, h_\nu) + \lambda_{\nu\pi}^0(p_\pi, h_\pi, p_\nu, h_\nu) + W(p_\pi, h_\pi, p_\nu, h_\nu\,)]^{-1}$$

where $\lambda_\pi^+(\lambda_\nu^+)$ is the internal transition rate for proton(neutron) particle-hole pair creation, $\lambda_{\pi\nu}^0(\lambda_{\nu\pi}^0)$ is the rate for conversion of a proton(neutron) particle-hole pair into a neutron(proton) particle-hole pair.Internal transition rate λ_π^+ for the creation of a proton particle-hole pair can be written by the following four terms:

$$\lambda_\pi^+(p_\pi h_\pi p_\nu h_\nu) = \frac{1}{\omega(p_\pi h_\pi p_\nu h_\nu E^{tot})} \begin{bmatrix} \int_{L_1^{p\pi}}^{L_2^{p\pi}} \lambda_{\pi\pi}^{1p}(u)\omega(p_\pi - 1, h_\pi, p_\nu, h_\nu, E^{tot} - u)\omega(1,0,0,0,u)du \\ + \int_{L_1^{h\pi}}^{L_2^{h\pi}} \lambda_{\pi\pi}^{1h}(u)\omega(p_\pi, h_\pi - 1, p_\nu, h_\nu, E^{tot} - u)\omega(0,1,0,0,u)du \\ + \int_{L_1^{p\nu}}^{L_2^{p\nu}} \lambda_{\nu\pi}^{1p}(u)\omega(p_\pi, h_\pi, p_\nu - 1, h_\nu, E^{tot} - u)\omega(0,0,1,0,u)du \\ + \int_{L_1^{h\nu}}^{L_2^{h\nu}} \lambda_{\nu\pi}^{1h}(u)\omega(p_\pi, h_\pi, p_\nu, h_\nu - 1, E^{tot} - u)\omega(0,0,0,1,u)du \end{bmatrix}. \quad ...(2)$$

In the above expression the second and fourth terms are for hole scatterings and the first and third termsare for particle scatterings. Here $\lambda_{\pi\pi}^{1p}(u)$ is the collision probability per unit time for a proton-proton interaction leading to an additional proton particle-hole pair. Similarly, $\lambda_{\nu\pi}^{1p}(u)$ is the collision probability per unit time for a neutron-proton interaction leading to an additional proton particle-hole pair. These collision probabilities per unit time in terms of effective squared matrix element M^2 are given below:

$\lambda_{\pi\pi}^{1p}\ (u) = \frac{2\pi}{\hbar} M_{\pi\pi}^2 \omega(2, 1, 0, 0, u)$,

$\lambda_{\pi\pi}^{1h}\ (u) = \frac{2\pi}{\hbar} M_{\pi\pi}^2 \omega(2, 1, 0, 0, u)$,

$\lambda_{\nu\pi}^{1p}\ (u) = \frac{2\pi}{\hbar} M_{\nu\pi}^2 \omega(1, 1, 0, 0, u)$,

$\lambda_{\nu\pi}^{1h}\ (u) = \frac{2\pi}{\hbar} M_{\nu\pi}^2 \omega(1, 1, 0, 0, u)$,

$\lambda_{\pi\nu}^{1p1h}\ (u) = \frac{2\pi}{\hbar} M_{\pi\nu}^2 \omega(0, 0, 1, 1, u)$,

Here $M_{\pi\pi}^2, M_{\nu\pi}^2$, $M_{\pi\nu}^2$ are the average squared matrix elements of the residual interactions which depend on the total energy E^{tot} of the composite nucleus. If we consider two-component matrix elements in terms of an average M^2 then,

$M_{\pi\pi}^2 = R_{\pi\pi}M^2$,

$M_{\nu\nu}^2 = R_{\nu\nu}M^2$,

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In TALYS calculation, we take the default values, $R_{\nu\nu} = 1.5$, $R_{\pi\pi} = R_{\pi\nu} = R_{\nu\pi} = 1$ but these parameters are adjustable. The following semi-empirical expression for the squared matrix element has been found to work well for the incident energy between 7 and 200 MeV:

$$M^2 = \frac{C_1 A_p}{A^3}\left[7.48C_2 + \frac{4.68\times10^5}{\left(\frac{E^{tot}}{n.A_p}+10.7C_3\right)^3}\right] \qquad ...(3)$$

Here C_1, C_2 and C_3 are the adjustable constants[9,10].

4 Results and Discussion

In the present study, the proton spectra for the ^{59}Co(n,xp) reaction at the incident beam energies of 37.5, 41.0, 45.0, 49.0, 53.5 and 62.7 MeV have been calculated. As discussed above, we have considered two particle exciton model for the pre-equilibrium contribution. The final results from the calculations are compared with the available experimental data from EXFOR[3,4] in the following figures. In this work we have fitted the value of average squared matrix element M^2 using hit and trial method.

From Figs 1-6, it is clear that there is a good agreement between the experimental data and theoretical prediction after making use of appropriate value for M^2. It is clear from the figures that high energy tail has a significant amount of contribution from pre-equilibrium nuclear reaction mechanism. The best fit values for M^2 are presented in Table 1. It is observed that with increase in incident beam energy range of outgoing proton energy also increases, while

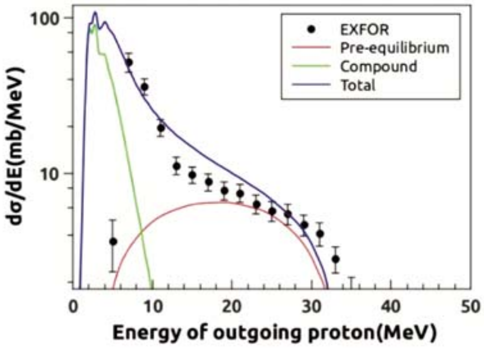

Fig.1 – Proton spectra for ^{59}Co(n,xp) atincident energy 37.5 MeV

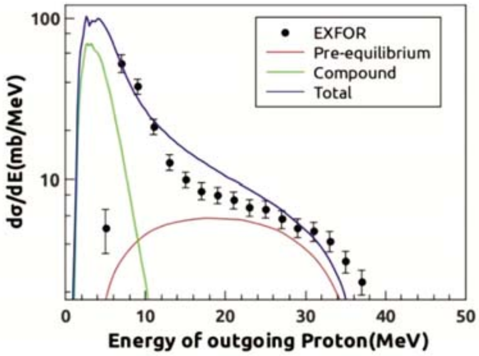

Fig.2 – Proton spectra for ^{59}Co(n,xp) atincident energy 41.0 MeV

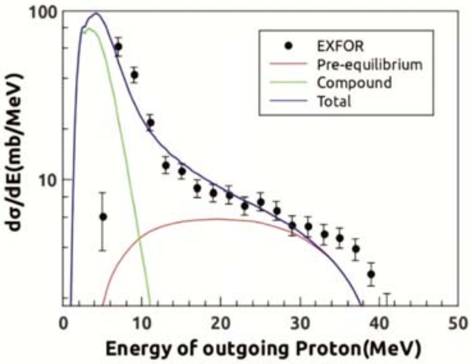

Fig.3 – Proton spectra for ^{59}Co(n,xp) atincident energy 45.0 MeV

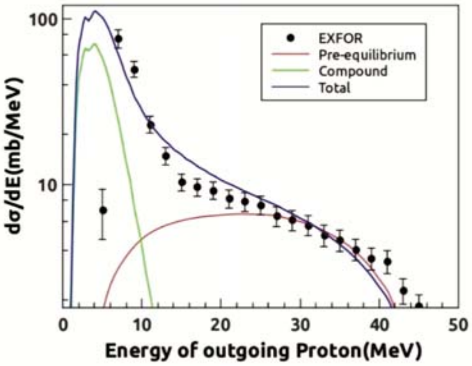

Fig.4 – Proton spectra for ^{59}Co(n,xp) at incident energy 49.0 MeV

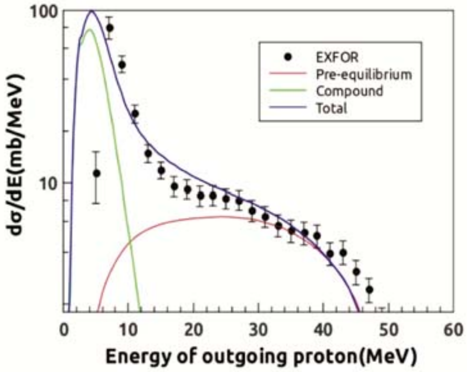

Fig.5 – Proton spectra for ^{59}Co(n,xp) at incident energy 53.5 MeV

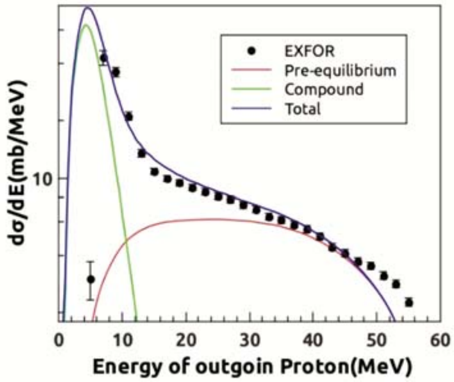

Fig.6 – Proton spectra for ^{59}Co(n,xp) at incident energy 62.7 MeV

Table1 – Best fit values for M^2 at different beam energy for the ^{59}Co(n,xp) reaction.

Incident energy (MeV)	M^2
37.5	0.00023755
41.0	0.000237366
45.0	0.000203296
49.0	0.000215119
53.5	0.00014369
62.7	0.000105954

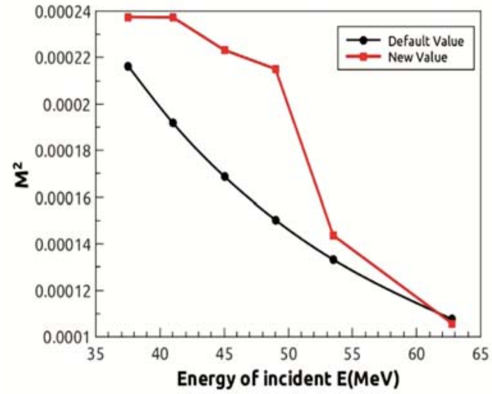

Fig.7 – Comparison between the default and new squared matrix element M^2.

the maximum energy of outgoing proton through compound nucleus is ~11 MeV.

The calculation for M^2 is done for n = 3, where 'n' is the exciton number and n = 3 (2p,h) is the first case in nucleon induced reaction[5]. After multiple interaction of excitons in the nucleus, the number of excitons changes. The change will be as $\Delta n = +2$ for a new particle-hole pair or $\Delta n = -2$ for an annihilation of a particle-hole pair or $\Delta n = 0$ for creation of a different configuration with the same exciton number. The default value for M^2 is not sufficient to reproduce the experimentally observed trends. Therefore, the calculations have been carried out using the best fitted value for M^2 (see Fig. 7).

5 Conclusions

It is clear from this study that pre-equilibrium reaction play an important role in the ^{59}Co(n,xp) reaction. The squared matrix element M^2 given by default value is not sufficient for reproducing the experimentally observed trends of the emitted proton spectra. By adjusting the M^2 values, we have obtained good predicted values on the basis of exciton model. The present work also suggests that the exciton model works well for the ^{59}Co(n,xp) system within the range of incident projectile energies from 37.5 to 62.7 MeV. It is concluded that pre-equilibrium contributions increase with increase in incident energy of the neutron.

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References

1 Gandhi A, Sharma A, Kopatch Y N, Fedorov N A, Grozdanov D N, Ruskov I N & Kumar A, *J Radioanal Nucl Chem*, 322 (2019) 89.

2 Gandhi A, Rai N K, Prajapati P K, Nayak B K, Saxena A, Roy B J, Singh N L, Mukherjee S, Kopatch Y N, Ruskov I N, Grozdanov D N, Fedorov N A & Kumar A, *Indian J Phys*, 93 (2019) 1345.

3 Otuka N, Dupont E, Semkova V, Pritychenko B, Blokhin A L, Aikawa M, Babykina S, Bossant M, Chen G, Dunaeva S, Forrest R A, Fukahori T, Furutachi N, Ganesan S, Ge Z, Gritzay O O, Herman M, Hlavac S, Kato K, Lalremruata B, Lee Y O, Makinaga A, Matsumoto K, Mikhaylyukova M, Pikulina G, Pronoyaev V G, Saxena A, Schwerer O, Simakov S P, Soppera N, Suzuki R, Takacs S, Tao X, Tarkanyi F, Varlamov V V, Wang J, Yang S C, Zerkin V & Zhuang Y, *Nucl Data Sheets*, 120 (2014) 272.

4 EXFOR data base "https://www-nds.iaea.org/exfor/".

5 Home page link IAEA- "https://www-nds.iaea.org/".

6 Koning A J, TALYS user manual- A nuclear reaction program (2011).https://doi.org/10.1016/j.nds.2012.11.002.

7 Koning A J, Hilaire S & Duijvestijn M C, "TALYS-1.0", Proceedings of the International Conference on Nuclear Data for Science and Technology, April 22-27, 2007, Nice, France, Edn, Bersillon O, Gunsing F, Bauge E, Jacqmin R & Leray S, *EDP Sci*, (2008) 211.

8 Voinov A V, Grimes S M, Brune C R, Bürger A, Görgen A, Guttormsen M, Larsen A C, Massey T N, Siem S & Kalbach C, *Phys Rev C*, 83 (2011) 054605.

9 Kalbach C, *Phys Rev C*, 33 (1986) 818.

10 Koning A J & Duijvestijn M C, *Nucl Phys A*, 744 (2004) 15.