# Thick and thin target $^7$Li(p,n)$^7$Be neutron spectra below the three-body break up reaction threshold

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## I. Introduction

In India, the 14 UD Pelletron Accelerator at the Tata Institute of Fundamental Research, Mumbai (BARC-TIFR Pelletron) and Folded Tandem Ion Accelerator at the Bhaba Atomic Research Centre (BARC-FOTIA) are main accelerators which serve as $^7$Li(p,n)$^7$Be neutron sources for neutron induced reaction cross section measurements. Various activation cross section measurements have been performed for neutron captures up to $E_n$~17 MeV with these neutron sources [1]. Since the TOF and multiple foil activation techniques cannot be applied at these accelerators due to the continuous beam structure and weak neutron flux, we have to rely on calculated neutron energy spectra for subtraction of the $^7$Li(p,n$_1$)$^7$Be contribution. We, therefore, developed a new deterministic code **EPEN – E**nergy of **P**roton **E**nergy of **N**eutron.

## II. Formalism

The formalism adopted in the present work is very similar to the formalism adopted by Lee and Zhou[2]. However, there are two main differences (1) the kinematic equations are written in terms of $^7$Li mass rather than $^7$Be($m_{Be}=m_{Li}+m_p-m_n$) everywhere due to the fact that the $^7$Li mass is more accurate by an order of two, (2) we are unable to reproduce the results presented by Lee and Zhou (see Fig.4 of [2] ) using their adopted kinematic equations and the "±"selection criteria prescribed by them in the double-valued region. Their formalism always yield a dip around 30 keV in the differential neutron energy spectrum near threshold. We therefore prescribe our own "±" selection criteria in the double-valued region. Below the threshold of the three-body break-up reaction, the neutron production is described by the two-body kinematics for $^7$Li(p,n$_0$)$^7$Be and $^7$Li(p,n$_1$)$^7$Be. The double differential neutron yield for one incident proton is

$$d^2Y(\theta, E_n)/dE_n d\Omega = (dE_p/dE_n)\,(-dx/dE_p)\,\rho\,(d\Omega_{cm}/d\Omega) d\sigma(E_p,\theta)/d\Omega_{cm}, \qquad (1)$$

where $\rho$ is the volume number density of $^7$Li nuclei, $x$ is the thickness of the lithium target, $\Omega$ and $\Omega_{cm}$ are the solid angles of outgoing neutrons in the laboratory and centre-of-mass system, $d\sigma(E_p,\theta)/d\Omega_{cm}$ is the angular differential cross section of the neutron in the centre-of-mass system. The quantity $(-1/\rho)(dE_p/dx)$ is known as the stopping power which is obtained from SRIM [3] and $(dE_p/dE_n)\ (d\Omega_{cm}/d\Omega)$ is the product of the Jacobians. For the near threshold region, the functional form suggested by Macklin and Gibbons was adopted for the (p,n$_0$) reaction. Above 1.95 MeV, the angular differential cross sections of the $^7$Li(p,n$_0$)$^7$Be and $^7$Li(p,n$_1$)$^7$Be reactions evaluated by Liskien and Paulsen were adopted [4]. The $^7$Li(p,n$_0$)$^7$Be differential cross section between 1.92 MeV and 1.95 MeV were obtained by cubic spline fits.

## III. Results and Discussion

### III.1 Comparison of our results with experimental results

To validate our result, we compare our thick target $^7$Li(p,n$_0$)$^7$Be neutron spectrum ($E_p$=1912 ±0keV) for the lithium sample (100 μm thick) with those measured by Lederer *et al.* [5], Ratynski *et al.* [6], Feinberg *et al.* [7] in Fig. 1. Our result agrees with the measured spectra except for broader low- and high-energy tail observed by Feinberg *et al.* [7]

which is due to the relatively thick $^6$Li-glass detector and its effects on the time-of-flight resolution.

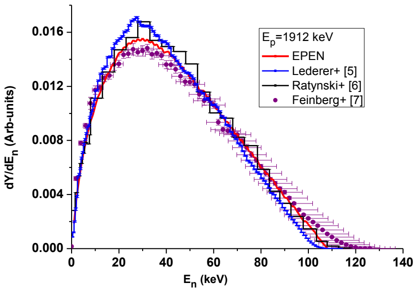

*Fig. 1: Comparison of EPEN $^7$Li(p,n$_0$)$^7$Be neutron energy spectrum at E$_p$=1912 ± 0 keV with experimental results [5-7] for a thick natural lithium target.*

Fig. 2 shows comparison between our result and Kononov *et al.*'s experimental [8] result of zero degree neutron yield for $^7$Li(p,n)$^7$Be reaction near threshold, for a thick lithium target.

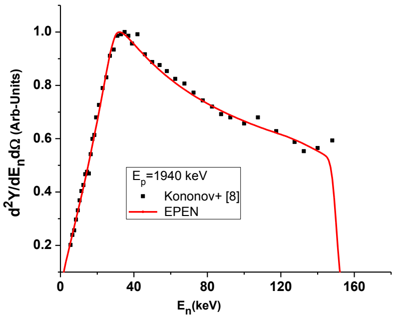

*Fig. 2: Comparison of EPEN $^7$Li(p,n$_0$)$^7$Be neutron 0 ± 5° double differential energy spectrum at E$_p$=1940 keV with experimental result [8] for a thick natural lithium target.*

### III.2. Neutron spectrum at E$_p$=3.8 MeV

Fig. 3 shows EPEN neutron energy spectra for proton bombarding energy 3.8 MeV with maximum angular coverage of 26.8 degree. The thickness of the lithium target is 38 micron.

The EPEN code will be free for distribution, and the source codes and input data may be downloaded from the EPEN web site (http://mzu.edu.in/index.php/physics-epen).

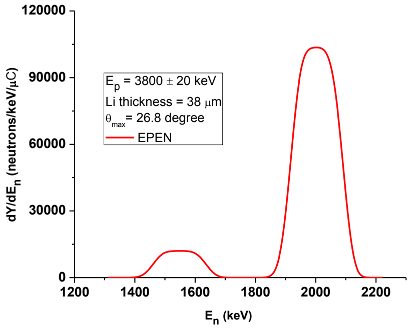

*Fig. 3: EPEN neutron energy spectra for thin lithium target thickness 38 μm at E$_p$ =3800±20 keV and angular coverage of 26.8 degree.*

## References

[1] H. Naik *et al.*, J. Radioanal. Nucl. Chem. **293**, 469 (2012); P.M. Prajapati*et al.*,Eur. Phys. J. A **48**, 35 (2012); H. Naik*et al.*,Eur. Phys. J. **47**, 51 (2011); Rita Crasta*et al.*, Ann. Nucl. Energy**47**, 160 (2012); SadhanaMukerji*et al.*,Pramana**79**, 249 (2012); V.K. Mulik*et al.*, Ann. Nucl. Energy **63**, 233 (2014); R.Crasta *et al.*, Nucl. Sci. Eng. **178**, 66 (2014).

[2] C.L. Lee and X.L. Zhou, Nucl. Instr. Meth. Phys. Res.B **152**, 1 (1999).

[3] James F. Ziegler and J.P. Biersack, SRIM - The stopping and range of ions in matter, SRIM-2013.00 version,2013.

[4] H. Liskien and A. Paulsen, At. Data Nucl.Data Tables **15**, 57 (1975).

[5] C.Lederer,F. Käppeler, M. Mosconi, R. Nolte, M. Heil, R. Reifarth, S. Schmidt, I. Dillmann, U. Giesen, A. Mengoni, and A. Wallner, Phys. Rev. C **85**,055809 (2012).

[6] W. Ratynski and F.Käppeler, Phys.Rev.C **37**, 595 (1988).

[7] G. Feinberg,M. Friedman, A. Krasa, A. Shor, Y. Eisen, D. Berkovits, D. Cohen, G. Giorginis, T. Hirsh, M.Paul, A.J.M. Plompen, E. Tsuk, Phys. Rev.C**85**, 055810 (2012).

[8] V.N. Kononov, E.D. Poletaev, and B.D. Yurlov, Sov. At. Energy**43**, 947 (1977).