Quasi-monoenergetic neutrons from p+^{7}Li

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Introduction

The neutrons emitted from ^{7}Li(p,n)^{7}Be reaction near threshold have been used to experimentally reproduce the stellar nucleosynthesis s-process. Thick target low energy neutron yield is also useful for BNCT (Boron Neutron Capture Therapy) due to the rapid rise in the cross section near threshold. If the lithium target is thin enough (3-5 μm), the ^{7}Li(p,n)^{7}Be reaction can be used to produce quasi mono-energetic neutrons at different energies. We have simulated the neutron emission spectra from ^{7}Li(p,n)^{7}Be reaction, for thin targets at 3.5, 18.0, 36.4, 48.0 and 62.9 MeV and for thick targets at 2.0 MeV. The reaction has a Q-value of -1.644 MeV and threshold energy (E_{th})=1.88 MeV. Depending on the projectile energy the residual ^{7}Be can be formed in ground state or one of its excited states. For different states the Q value, threshold energy and cross-sections will change accordingly, and we get different sets of neutrons. Due to the reduction of cross-section, neutron flux from higher excited become lower.

Formulation of the code

For a given proton energy E_p, the neutron energy (E_n) at a given emission(θ)angle is given by:

$$\sqrt{E_n} = \frac{\sqrt{m_n m_p E_p}cos\theta \pm \sqrt{m_n m_p E_p cos^2\theta + (m_R + m_n)\{E_p(m_R - m_p) + Q m_R\}}}{m_R + m_n}$$

energy of the incident proton decreases in the thick target the neutron energy also changes.

The double differential yield per projectile is given by[1]

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

where Ω and Ω_{cm} are the solid angles of outgoing neutrons in the laboratory and CM frames, $\frac{d\sigma(E_p,\theta)}{d\Omega_{cm}}$ is angular differential cross section of the neutron in the CM system. The expression of dE_p/dE_n can be obtained as

$$\frac{dE_p}{dE_n}\frac{d\Omega_{cm}}{d\Omega} = \pm\frac{(m_{Li} + m_p)^2(\mu \pm \xi)\gamma E_p}{m_p m_n E_p(\mu \pm \xi) \pm m_{Li}(m_{Li} + m_p - m_n)E_{th}}$$

where ξ is a function of m_p, m_{Li}, m_n, E_{th}, E_p and θ. $(-1/\rho)(dE_p/dx)$ is the mass stopping power. Angular differential cross sections are calculated for E_p<1.95 MeV. For 1.95<E_p<7 MeV data compiled by Liskien and Paulsen [2] are used.

For θ we have used 1^0interval spanning the range 0^0 to 180^0. For E_n, the interval is 1 keV for lower proton energies (<5 MeV) and 100 keV for higher proton energies(>15MeV).

The angle integrated spectra is given by

$$\frac{dY(E_n)}{dE_n} = \int d\Omega\frac{d^2Y(\theta,E_n)}{dE_n d\Omega}w_2\left(E_p(\theta,E_n)\right)$$

where $w_2\left(E_p(\theta,E_n)\right)$, the *weighting function*, is a function of proton energy. Shape of the weighting function depends on the energy distribution of the incident proton beam and thickness of the target. Two types of targets are considered- **1.** Target sufficiently thick to completely attenuate all the protons at least up to threshold energy, **2.** target thickness is such that all the protons penetrate the sample. Energy distribution of incident protons is assumed to be Gaussian with finite standard deviation. High energy neutron emission is forward peaked and it's preferable to use 0^0 neutrons. The spread of the quasi-monoenergetic peak increases with target thickness due to large variation of proton energy loss in the target.

Results

A total of three scenarios have been studied. Firstly, we have studied the thick target double differential and angle integrated yield at E_p between 1.89 and 2.0 MeV with Gaussian proton energy spread (σ=0.5%). Double differential yield has been studied for 1^0, 30^0, 60^0, 90^0, 120^0 and 150^0 (Fig. 1). Angle integrated spectra are calculated at 10 keV interval. The angle integrated spectra are quasi-Maxwellian in shape. At these proton energies only ground state of the residual nucleus is populated. In the second part neutron emission due to proton from 5μm, 10 μm, 15 μm and 35 μm target is simulated (Fig. 2). A Gaussian energy distribution with mean at 3.5 MeV and standard deviation 20 keV is considered for the proton beam. Maximum angle of coverage is taken as 26^0 [1]. The neutron emission spectra from the ground and the first excited states are simulated here. From this simulation we show that as target thickness decreases neutrons come closer to being quasi-monoenergetic. In the third case, the production of quasi-monoenergetic neutrons at higher energies has been considered (Fig. 3). We have considered incident proton energies 18, 36.4, 48.5 and 62.9 MeV and gaussian energy spread of with σ=1% of mean energy. Only the neutrons in a small angular spread at 0^0 are observed. At these energies several excited states of the residual nucleus are possible and we have observed the position and width of those peaks. The three body breakup threshold for the reaction is at 3.7 MeV. As a result, in practice a continuum at low energies results, which is not simulated.

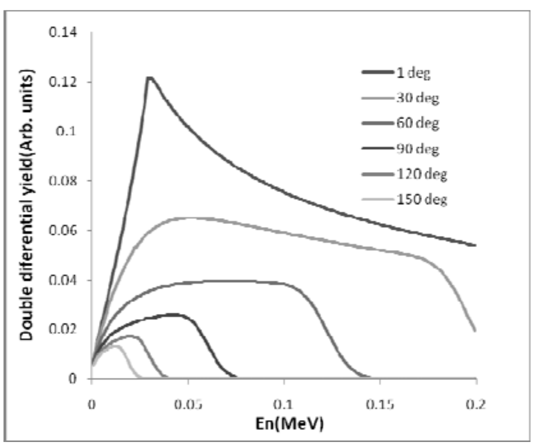

Fig. 1: Double differential neutron yield at different emission angles at E_p=2.0 MeV

Conclusion

p+^{7}Li reaction can be used as a source of quasi-monoenergetic neutrons at different energies. The spread in the neutron energy depends on the proton energy distribution and on the thickness of the Li target. We have developed a reaction code which produces the neutron energy angle distribution from the said reaction at different energies. The results of this code agree fairly well with the work from other authors.

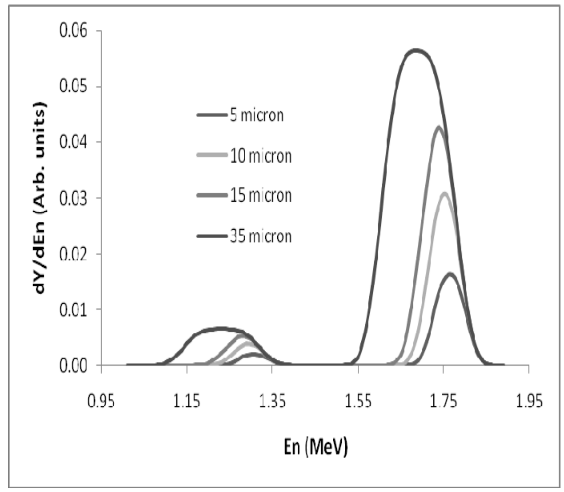

Fig. 2: Angle integrated neutron spectra for different thicknesses at E_p=3.5 MeV

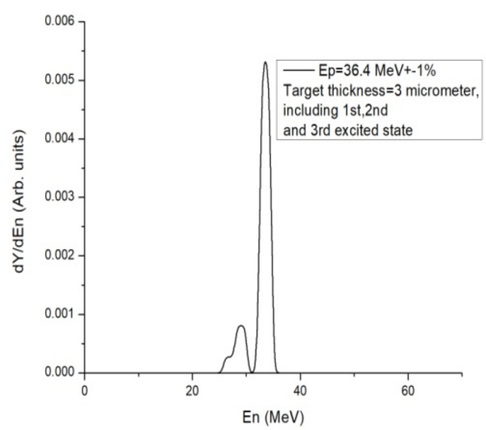

Fig. 3: Quasi-monoenergetic neutron spectra at E_p=36.4 MeV

References

[1] R. Pachuau et al, Nuclear Science and Engineering **187** , 70–80 (2017).

[2] Horst Liskien and Arno Paulsen, Atomic Data and Nuclear Data Tables **15**, 57-84 (1975)