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Development of a kinematically focused neutron source with the p(^{7}Li,n)^{7}Be inverse reaction

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ABSTRACT

Directional beams of neutrons can be produced, if a nuclear reaction, which emits neutrons, is initiated in inverse kinematics with a heavy ion projectile bombarding a light target. In this paper we investigate the use of the p(^{7}Li,n)^{7}Be inverse reaction to produce kinematically focused, quasi-mono-energetic neutron beams with a view to develop such an unusual neutron source for fundamental and applied nuclear physics studies. An experiment was carried out to validate the concept and to test the viability of two types of hydrogen-rich solid targets: polypropylene and TiH_2. Neutron time-of-flight/energy spectra at 3 m distance from the source have been measured at ^{7}Li bombarding energies of 13.5, 15, 15.5, 16, and 17 MeV, and neutron backgrounds from parasitic reactions have been characterized. The neutron angular distribution in the laboratory has been measured at 15 MeV. A Monte-Carlo code based on two-body relativistic kinematics has been developed and validated by comparison with the experimental data. Code-based extrapolations have then been used to deduce neutron energy spectra and maximum neutron fluxes available for future irradiation of samples placed in the neutron beam at small distances. For neutrons produced with thin (4 μm) and thick (28 μm) polypropylene targets the maximum available fluxes are calculated to be 10^7n/s/sr and 7×10^7 n/s/sr respectively. The development of a dedicated facility to produce kinematically focused neutrons is discussed.

1. Introduction

Conventional quasi-mono-energetic neutron sources produce neutrons isotropically via direct reactions on light nuclei, e.g. d(d,p)n or ^{7}Li(p,n)^{7}Be. The lack of directionality means that typically less than 1 percent of the produced source neutrons can be used for irradiating samples, the vast majority contributing to the room background instead.

However, natural collimation of neutron beams can be achieved, if the neutrons are produced using a reaction in inverse kinematics, where the projectile is much heavier than the target. Neutron production via this method thus combines the best features of white neutron sources (collimated beams) and conventional quasi-mono-energetic neutron sources (high neutron fluxes at short distances).

Information in the literature concerning neutron production in inverse kinematics is rather sparse. Some test experiments performed in the early 1980s [1,2], but apart from that, little detailed research has been carried out. It is thus surprising that such an idea has not been developed further. At present dedicated facility to produce neutrons via this method does not exist.

To produce neutrons in inverse kinematics involves the use of reactions such as p(^{7}Li,n)^{7}Be in the 13–17 MeV energy range and thus requires a 9 MV tandem accelerator or 115 MeV cyclotron in order to accelerate $^7Li^{3+}$ ions up to these energies. Unfortunately, due to the worldwide closure of many accelerator laboratories over the last two decades, there is only a handful of accelerators left capable of producing focused neutrons via this method.

The kinematic focusing technique clearly offers some distinct advantages over standard isotropic quasi-monoenergetic sources:

1. The focusing enhances the available neutron flux by a factor of between 25 and 100.
2. The lack of neutron emission at most angles results in much lower fast and thermal scattered neutron backgrounds in the experimental hall.
3. The placement of sensitive detectors adjacent to the neutron source becomes feasible, without the necessity for heavy shielding.

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4. The produced neutrons lie in the energy range 0.5–4 MeV, exactly in the region of interest for fast Generation IV reactor concepts.

In this paper, we report on the results of an experiment designed to validate the viability of the concept and aid the choice of design parameters for the development of a dedicated kinematically focused neutron source at IPN Orsay. This neutron source is intended for performing fundamental studies of the nuclear fission process and associated nuclear data measurements related to 4th generation nuclear reactors. A first experimental program will involve the study of prompt γ−ray emission in fission, since the directional neutron beam will allow the placement of γ−ray detectors out-of-flux but adjacent to the sample to be irradiated.

However, other potential applications of such unique neutron sources cover several different research fields and include non-destructive assay of nuclear waste, irradiation for the aerospace industry, medical imaging, neutron capture therapy and the characterization of new types of detectors.

2. Inverse kinematics

The main advantage of inverse kinematics is the natural forward collimation of the reaction ejectiles. The heavier the projectile nucleus, the better the collimation. For reactions, which eject neutrons, this will induce a large enhancement of the neutron fluxes at 0° in the laboratory frame.

2.1. The p(^{7}Li,n)^{7}Be reaction

The p(^{7}Li,n)^{7}Be reaction [3] is one of the most commonly used ones in direct kinematics to produce mono energetic neutrons, especially below 0.7 MeV. Table 1 gives a summary of the important characteristics of this reaction when run in inverse kinematics. At the reaction threshold of 13.098 MeV a mono energetic neutron of 1.44 MeV is produced. With increasing beam energy new outgoing channels open such as the production of the recoil nucleus ^{7}Be in its first excited state at 0.429 MeV. The threshold energy for this channel is 16.513 MeV and the corresponding neutron energy is 3.84 MeV. Table 1 gives also an information on the next two open reaction channels. For a sufficiently high beam energy, these four different outgoing channels are competing with each other, which will complexify the neutron spectrum. For this reason our study is limited to ^{7}Li bombarding energies in the range of 13.098–16.513 MeV, where the kinematics of the outgoing neutrons can easily be predicted.

The results of 2-body relativistic kinematics calculations are shown in Fig. 1. The kinematic curves for a given bombarding energy have two distinct peaks in the laboratory frame corresponding to forward and backward emission of neutrons in the center of mass frame. The relative size of the principal (high energy) peak and satellite (low energy) peak is governed by both the relativistic kinematics of the focusing *and* the angular distribution of emission in the centre of mass frame, which changes drastically as a function of ^{7}Li bombarding energy, as we shall see later.

Table 1
Main characteristics of the p(^{7}Li,n)^{7}Be reaction. Neutrons produced in each channel are labeled n_i to indicate they are produced with different kinematics.

Type of exit channel	Q-value (MeV)	Threshold energy (MeV)	Primary 0° neutron energy
$n_0 + {}^7_4$Be	−1.644	13.098	1.44
$n_1 + {}^7_4$Be*(0.429 MeV)	−2.073	16.513	3.84
$n_2 + {}^3_2$He + ${}^4_2$He	−3.230	25.726	8.18
$n_3 + {}^7_4$Be*(4.57 MeV)	−6.214	49.489	18.79

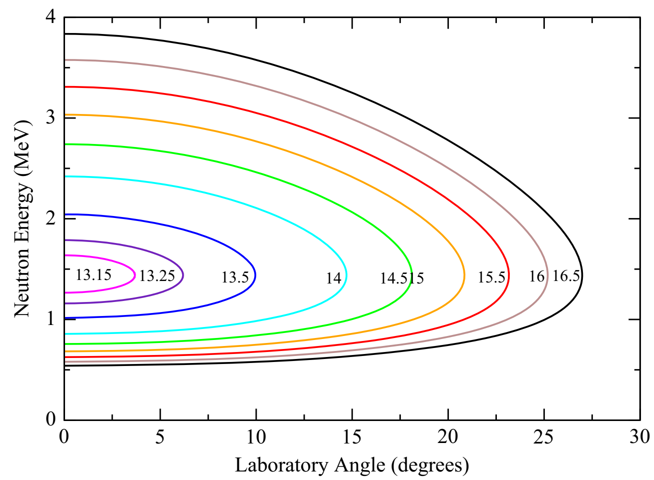

Fig. 1. Kinematic curves relating the angle of neutron emission to neutron energy in the laboratory frame for different ^{7}Li bombarding energies from 13.15 to 16.5 MeV, calculated using two-body relativistic kinematics.

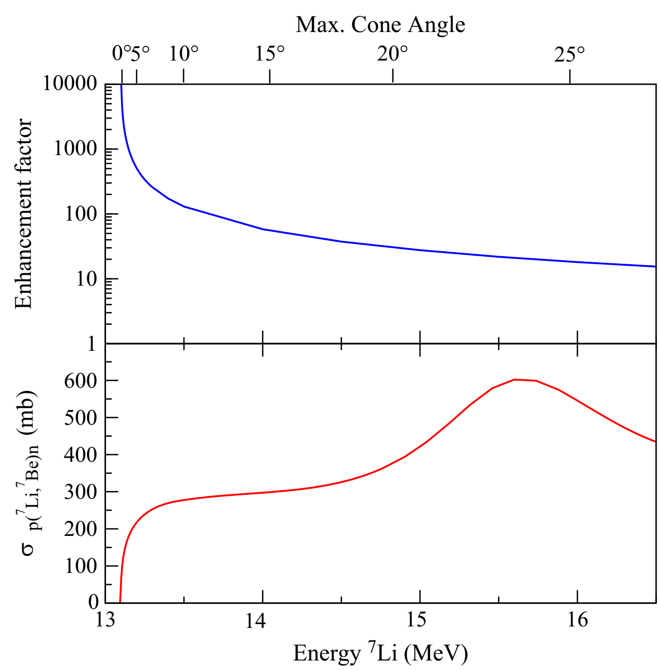

Fig. 2. The top panel shows the enhancement factor of the neutron flux between the inverse kinematic and the direct kinematic reaction as a function of ^{7}Li bombarding energy. The bottom panel shows the p(^{7}Li,^{7}Be)n reaction cross-section over the same energy range.

The picture is further complicated by the energy loss and straggling of ^{7}Li in the target and the fact that the neutrons originate from a non-punctual source, but a beam spot of finite size ($\sim$0.8 cm). These effects deteriorate the energy resolution of the neutron beam.

The gain from the focusing and natural collimation can be expressed in terms of neutron flux enhancement over the non-inverse reaction (see Fig. 2).

To obtain this curve, the reaction rates have been calculated for different ^{7}Li kinetic energies. The neutron flux per steradian has been normalized to the ^{7}Li beam intensity. At threshold the enhancement factor is maximal, since the emitted neutrons move