INTRODUCTION

Neutron energy spectra at different emission angles, between 0 and 120 degrees from the Be(p,xn) reaction generated by a beryllium thick-target bombarded with 5 MeV protons, have been measured at the Legnaro Laboratories (LNL) of the Italian National Institute for Nuclear Physics research (INFN). A new and quite compact recoil-proton spectrometer, based on a monolithic silicon telescope, coupled to a polyethylene converter, was efficiently used with respect to the traditional Time-of-Flight (TOF) technique. The measured distributions of recoil-protons were processed through an iterative unfolding algorithm in order to determine the neutron energy spectra at all the angles accounted for. The neutron energy spectrum measured at 0° resulted to be in good agreement with the only one so far available at the requested energy and measured years ago with TOF technique. Moreover, the results obtained at different emission angles resulted to be consistent with detailed past measurements performed at 4 MeV protons at the same angles by TOF techniques.

MATERIALS AND METHODS

The neutron spectra were measured with a recoil-proton spectrometer based on a silicon detector, which was developed by Agosteo et al. [1] for neutron spectrometry in the MeV range. The detection system consists of a monolithic silicon telescope 1 mm² in sensitive area coupled to polyethylene converter 1 mm in thickness.

The telescope consists of a ΔE and an E stages (about 2 μm and 500 μm in thickness, respectively) made out of a single silicon wafer and separated by a highly doped p⁺-common electrode [2]. As it was demonstrated by Agosteo et al. [1], this detection system is capable of discriminating effectively recoil-protons (produced by neutrons within the plastic converter) from secondary-electrons generated by background photons. The discrimination is performed by correlating event-by-event the energy deposited within the two stages by secondaries (recoil-protons and electrons). This task is carried out by filtering the signals generated by a particle impinging on the detector stages with two independent electronic chains and by acquiring the shaped pulses in coincidence mode through a 2-channel multichannel analyzer.

The energy distributions of the neutron yield were reconstructed with an unfolding algorithm based on a non-linear least-squares method. The response matrix was calculated through an analytical model developed by Agosteo and Pola [3] which gives the detector response as a function of the neutron energy. The initial guess for the iterative unfolding procedure was uniform in energy. The statistical uncertainties were calculated through a sensitivity analysis by sampling the corresponding experimental pulse height distributions within their standard deviation. The contribution of the uncertainty related to the irradiation position was also accounted for.

The neutron spectrum measured at 0° with the silicon-based system is compared in figure 1 with that measured by Howard et al. [4] with Time-of-Flight (TOF) technique.

Fig. 1. Distribution of neutron yield measured with the silicon telescope at 0° (black curve) compared with that obtained through TOF by Howard et al. [4] (gray curve).

The agreement of the unfolded spectrum with the literature data is satisfactory at energies higher than about 300 keV. This limit is due to the attenuation of recoil-protons in the air gap between the converter and the device (about 0.5 mm in thickness) and in the titanium-based dead-layer placed above the ΔE stage (about 0.25 μm in thickness).

RESULTS

The energy distribution of the neutron yield was measured at 0°, 20°, 40°, 60°, 80°, 90°, 100° and 120° by using an automatic positioning system. The distance between the beryllium target and the detector surface was about 5 ± 0.1 cm, corresponding to an angular resolution of
about 0.6°. The double differential distribution of the neutron yield, resulting from unfolding the experimental data, is shown in figures 3 and 4.

Fig. 3. Distribution of neutron yield measured with the silicon telescope at the emission angles 0°, 20°, 40°, 60°.

Fig. 4. Distribution of neutron yield measured with the silicon telescope at the emission angles 80°, 90°, 100° and 120°.

From the kinematics of the $^9$Be(p,xn)$^9$B reaction, it turns out that the maximum neutron energies are about 3.2, 3.1, 3.0, 2.7, 2.5, 2.3, 2.2, 2.1 MeV, respectively, which are in a satisfactory agreement with the measured ones.

As already mentioned, the yield of neutrons generated from 5 MeV protons on beryllium can be compared with literature data only at 0° (see figure 1). For larger angles, the neutron-yield versus neutron-energy trend is consistent with former measurements performed at 4 MeV protons with the TOF techniques (see figure 5) as reported in Howard et al. [4]. The comparison for the other angles may be done by retrieving the original measurements data through the Experimental Nuclear Reaction Data at EXFOR (CSISRS) database.

Fig. 5. Energy distribution of the yield of neutrons generated at different angles by 4 MeV protons striking a thick-beryllium target, measured with TOF by Howard et al. [4].

CONCLUSIONS

A characterization of the Be(p,xn) double differential yield of neutrons produced by bombarding a thick beryllium target with 5 MeV protons was performed. The energy distribution of neutron yield was measured in the angular range 0°-120° with a recoil-proton spectrometer based on a monolithic silicon telescope, which has a lower detection threshold of 270 keV. The neutron energy spectrum measured at 0° results to be in good agreement with literature data measured with time-of-flight techniques.