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An improved experimental set-up for (n,xn) reaction studies

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The (n,xn) reactions play an important role in many nuclear applications like accelerator-driven systems, fast neutron reactors or nuclear medicine. Their experimental study is necessary to improve and validate simulation models especially between about 10 MeV and 200 MeV where the pre-equilibrium process becomes significant and data are scarce.

A new experimental set-up has been built near the Tandem 7MV of Bruyères-le-Châtel (France) in order to perform new (n,xn) double-differential cross section measurements. It is composed of a 4π neutron detector and a low background neutron beam line. The detector, called CARMEN, is a tank containing 1 m^3 of Gd-loaded liquid scintillator. It is intended to neutron multiplicity distributions measurements event by event with a very high efficiency (85% to fission neutrons). Due to its high sensitivity, CARMEN requires a well collimated neutron beam line as well as a low background. The neutrons are produced by nuclear reactions between proton or deuteron primary beams and tritium or deuterium targets surrounded by a heavy concrete shielding through which a channel was made defining the neutron beam. Neutron beams between 4 and 25 MeV are thus available.

The entire set-up (detector and neutron production) and original experiments will be presented. The energy spectra of tagged (n,2n) reactions have been measured in the 8.3 - 13.3 MeV range on several targets. The results are compared with the predictions of the nuclear reaction code TALYS.

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1. Introduction

Reactions induced by neutrons are very important for many applications like Accelerator-Driven Systems, fast-neutron reactors or medical applications. Particularly, the (n,xn) reactions (induced by one neutron and emitting x neutrons) are the predominant non-elastic process for fast neutrons. For example in the 7-20 MeV energy range the (n,2n) reaction is one of the most important nuclear-reaction channels for non-fissile nuclei. The simulation codes are made of several models (optical model, direct interaction, pre-equilibrium and evaporation) to reproduce the whole reaction mechanism. Among these processes, the pre-equilibrium is clearly the least well known. Actually some of the existing models reproduce integrated observables but rarely differential measurements.

In order to constrain strongly the pre-equilibrium process we have performed an original programme to measure the energy spectra of neutrons in the (n,xn) reactions in coincidence with the neutron multiplicity. Contrary to “classical” (n,xn) reaction measurements where all the channels emitting at least one neutron are taken into account, we have extracted double differential cross-section in (n,2n) tagged reactions.

For this programme it was needed to build a set-up with a well-collimated neutron beam line and a neutron-detector assembly composed of NE213 cells and the 4π neutron detector CARMEN. In this paper we describe the detection set-up and the neutron beam line, and finally some results are shown.

2. Detection set-up

Our detection set-up (Fig. 1) can be divided into two main parts.

The first one consists of neutron detectors 1 m from the studied sample at 40°, 60° and 80° with respect to the beam direction. They are NE213 liquid scintillator cells (Φ=12.5 cm and L=5 cm) coupled to Photonis XP4512B phototubes. A pulse shape analysis allows neutron-gamma discrimination while the neutron energy is determined by time-of-flight (TOF). The detection threshold is tuned at 500 keV to ensure good n-γ discrimination. The efficiency is calculated with the O5S code [1].

The second part of the set-up is the 4π neutron detector CARMEN (Cells Arrangement Relative to the Measurement of Neutrons) [2]. It is a large spherical neutron detector operating like the BNB [3,4] or ORION [5, 6]. This kind of detector was already used in the past for (n,2n) integrated cross-section measurements [7]. It consists of two independent vertical hemispheres, 60 cm in outer-radius, 15 cm in inner-radius, each one filled with less than 0.5 m^3 of gadolinium-loaded scintillating organic liquid (BC521). A small space, about 10 cm, between the hemispheres allows double-differential cross sections measurements with the external NE213 detectors previously described. The 15 cm in radius area at the centre of the detector defines the reaction chamber. A horizontal channel, 5 cm in radius, allows the neutron to reach the reaction chamber, the beam exit being ensured by a rectangular wide-mouthed channel. Twelve phototubes surrounding each hemisphere collect the light produced in the scintillator.

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When a neutron enters the scintillating liquid it interacts with a proton whose recoil produces a so-called prompt light signal. The neutron is then slowed down by loosing its energy by inelastic and mainly elastic scattering on hydrogen and carbon nuclei. Since the neutron slows down to the thermal energy it can be captured by a gadolinium nucleus whose de-excitation produces a delayed light signal. Due to the low gadolinium concentration, 0.5 % by weight, 50 µs following the first interaction are necessary to capture 99% of the total number of captured neutrons in the scintillator. Several neutrons emitted simultaneously from the primary nuclear reaction are captured at different times and can be counted independently. For each event, two 50 µs gate signals (separated by 50 µs) are generated to measure the neutron and the background multiplicities respectively. The high efficiency of CARMEN, 85% for fission neutrons, makes it very sensitive to the neutron and gamma ray background.

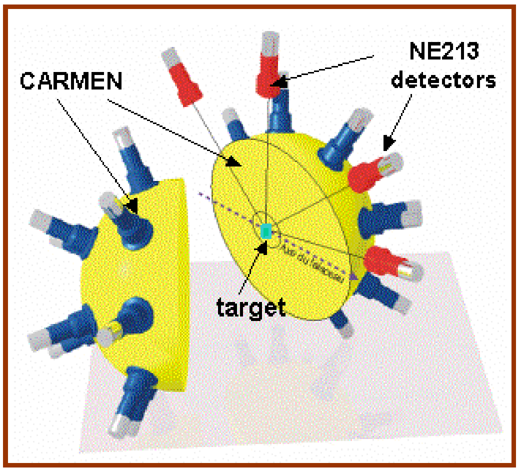

Figure 1: View of the detection set-up

The data acquisition is triggered by 1 neutron detected by a NE213 cell while CARMEN detects the (x-1) other neutrons of the reaction.

3. Neutron beam line

CARMEN is very sensitive to neutron and gamma rays, so its use required the construction of a dedicated neutron beam line. A detailed description can be found in the reference [8]; here we just remind the main features.

3.1 Description

A shielding structure was built with a bunker of concrete blocks assembled around the production target through which a channel was made to define the neutron beam. Neutrons are produced by nuclear reactions between accelerated proton or deuteron beams and a deuterium or tritium production-target. The ion beam is produced by the tandem VdG of Bruyères-le-Châtel accelerator between 4 and 12 MeV with typical beam intensities from 1 to 3 µA. The accelerator can deliver a continuous or pulsed beam, the nominal pulse frequency of 2.5 MHz can be divided by any integer number. In order to reduce the background, the beam was cut (by electrostatic deflection) during each 50 μs counting gates. A time pick-off was placed 1 meter upstream from the neutron production target to perform TOF measurements with a time resolution of 2 ns. Solid targets of Ti-deuteride or Ti-tritide manufactured by SODERN [9] and a deuterium gas target elaborated in the laboratory are used. The solid targets are 1 mg/cm^2 thick with an atomic ratio D/Ti and T/Ti precisely known and is up to 1.5. The gaseous target is a cylinder of 1 cm in diameter and between 1 and 6 cm long filled with deuterium at a pressure of 1.5 bars. The neutron energy covers the 4 - 25 MeV range by using T(p,n)^{3}He, D(d,n) ^{3}He and T(d,n) ^{3}He reactions.

3.2 Physical characteristics

The use of CARMEN requires a beam spatial extension smaller than 8 cm at the centre of the detector and a low neutron background. We decided that the capture rate in the liquid should be less than 0.1 count in 50 μs compared to the 1 neutron measured in an (n,2n) reaction. So the design of the bunker has been performed by calculations with the neutron transport code MCNP [10,11] with the hypothesis of sources of 10^8 n.s^{-1} in the 10-18 MeV range. The measured neutron-background capture-rate was between 0.05 and 0.15 count per 50 μs depending on the neutron source energy. The beam profile was measured along the beam axis at a distance of 3.40 m from the production target by a small C_6H_6 detector. Measurements were performed at several vertical and horizontal positions in the plane perpendicular to the beam axis. The figure 2 shows the very good agreement between the experimental points and the results of the simulation. At the centre of CARMEN, the beam diameter FWHM is 6 cm.

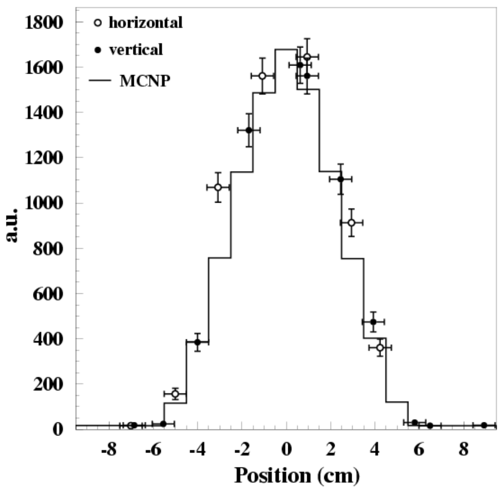

Figure 2: Measured (points) and simulated (histogram) spatial extension of the neutron beam at the centre of CARMEN.

The neutron beam flux and energy spectra have been measured with a NE213 neutron detector similar to those described in section 2. The energy was determined by TOF over distances between 5 and 10 meters depending on the neutron energy. Some spectra obtained with the gaseous deuterium target are presented on the figure 3. Due to the break-up reactions D(d,np)D, purely monokinetic beam can not be achieved for energies greater than 7 MeV. Particularly, the neutron beam of 13.5 MeV is produced with quite large break-up reactions at low energy. Such a flux can be used with the CARMEN detector, the prompt peak being used to select the monokinetic component by TOF. With a cylindrical (Φ=1 cm and L=6 cm) gaseous target, the monokinetic neutron flux on the studied sample (3.40 m far from the target production) was of about 1000 $n\cdot cm^{-2}\cdot s^{-1}$.

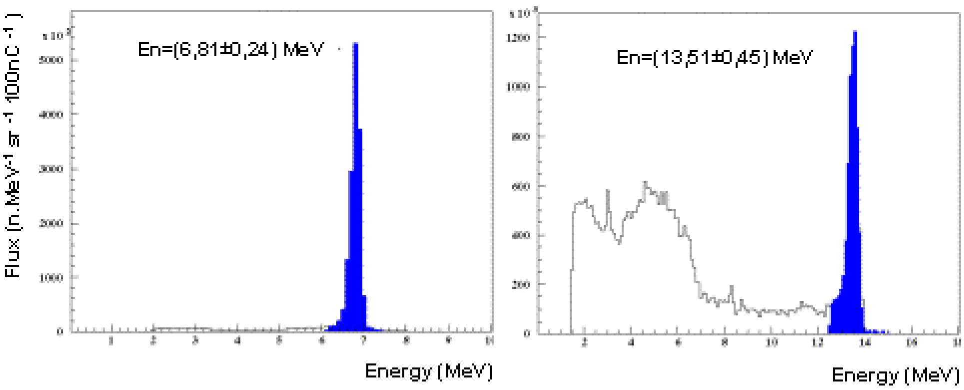

Figure 3: Energy spectra of neutron beams for 4 MeV and 11 MeV deuterons on gaseous deuterium target.

4 Results

Measurements have been performed between 8.3 and 13.3 MeV on Bi and Ta targets of 255 g and 65 g respectively. The figure 4 shows (n,xn) and (n,2n) spectra obtained by a double TOF technique. The prompt peak from CARMEN is used to select the monokinetic component by TOF, and the NE213- accelerator TOF allows to measure the neutron energy. The lines represent the double differential-cross section predicted by TALYS[12]. The evaporation and pre-equilibrium (two components exiton model) parts are also drawn. The elastic scattering peak is not measured because of the low energy resolution measurement due to the small target-detector distance and the 2 ns deuteron beam time resolution. TALYS underestimates slightly experimental results especially at forward angles where pre-equilibrium emission is important.

The extraction of the energy spectra in (n,2n) reactions requires special treatments described in details in ref. [2]. The neutron background distribution and the CARMEN efficiency are taken into account. The slope and the maximum of the spectra are well reproduced by the calculations. A brutal discontinuity appears in the code prediction in the high energy part of the (n,2n) spectra. Actually to save computer time, the less populated reaction channels are no more calculated under a fixed threshold. To simulate the (n,2n) exclusive channels this threshold should be decreased. Despite this problem, data and TALYS calculations are in good agreement.

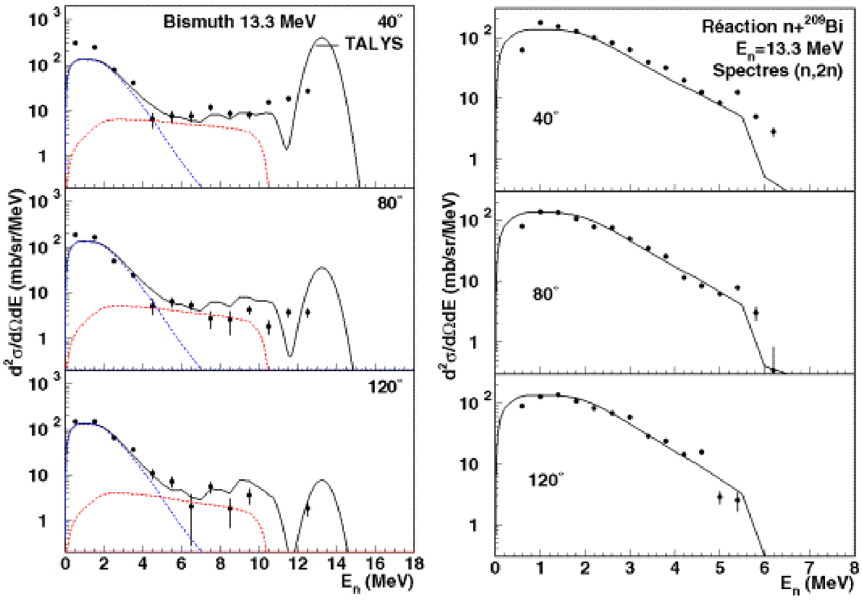

Figure 4: Double differential cross section in (n,xn) reactions (left) and in (n,2n) reactions (right) for (13.3 MeV) neutron on Bi target. The lines are the TALYS code predictions, the blue and red correspond to evaporation and pre-equilibrium processes respectively.

5 Conclusion

An original measurement of the neutron energy spectra in (n,xn) reactions in coincidence with the neutron multiplicity has been performed. This experiment has required the construction of a 4π neutrons detector CARMEN and a dedicated neutron beam line. The characteristics of the neutron beam, good collimation, low neutron background and energy available between 4 and 25 MeV are well adapted to the use of CARMEN. The energy spectra of neutrons emitted in tagged (n,2n) reaction have been measured between 8 and 13.3 MeV. The results are in good agreement with the TALYS code.

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