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Neutron production with particle accelerators

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Abstract. Neutron beams have been produced at Laboratory of High Energy Physics (LHEP) of University of Bern. LEHP is equipped with an 18 MeV cyclotron with an external beam line. Simulations, analytical calculations and kinematics studies have been carried out, in order to produce several neutron beam configurations with characteristics suited for specific applications. Furthermore, a procedure for energy modulation has been developed to match the fixed cyclotron energy to the needed requirements. The technique described in this work is of general application and can be applied to more intense beams up to 10^{10} pps.

1. Introduction

Neutrons are of primary interest in many areas of basic and applied physics. Their production and detection still represents an uneasy task. This is due to its peculiar behavior, which is very different from that of charged particles, X and gamma rays. Neutrons interact with matter through nuclear force only and the reaction cross sections are strongly energy dependent [1].

Neutrons can be produced by means of radioactive sources (such as ^{252}Cf), nuclear reactors or particle accelerators. The major disadvantage in using nuclear reactors lies in the huge amount of gamma rays produced both by fission and interactions between neutrons and fission fragments in the core. This results in a very broad spectrum, which is not always desired. Instead, different types of incident particles can be used with particle accelerators to produce neutrons. These are, for example, protons, alpha particles, deuterium or tritium. In this work, the neutron production was carried out with protons from a cyclotron.

One of the main reasons why different aspects of neutrons production have been studied in this work is related to the low number of facilities dedicated to this topic. In fact, in Italy there are no facilities specifically qualified for the neutron production. Nevertheless, Italy is the third user in the world of ISIS (Neutron and Muon Source - Oxford UK) and the fifth European nation in number of publications [2].

A second motivation for this work is the growing interest in nuclear applications involving neutrons in a very wide energy spectrum (from thermal to fast and relativistic neutrons). Neutron applications cover several fields, ranging from industry to research and medicine: fast neutron cancer therapy, isotope production, measurement of dose administrated to aviation personnel, heritage studies on precious and delicate objects or works of art, radiation hardness, science and chemistry of materials, material recognition, nuclear astrophysics and so on. A considerable requirement comes from the field of basic research: it is an example the SPES project at Legnaro National Laboratories (LNL) [3].

New production methods have been studied in order to carry out neutron beams with the best characteristics suitable for the users.

2. Preparatory study

The characterization of neutron beams produced with accelerators needs measurements of the energy spectrum at different angles. The energy of the neutrons produced is strictly related both to the features of the target (density, thickness, etc ...) and the energy of the projectiles. Since the production rate can vary a lot with the solid angle covered by the detector, it is fundamental to know the distance between the source and the detector.

Several targets have been used to produce the neutron beams. We identified the appropriate energy range for the targets studied by calculating the output energy of the neutrons. The simulations needed for the calculation of the reactions cross section, kinematics and energy loss in the media were made with *cross section plotter*, *Trim* and *Lise++* [4, 5]. On the basis of the simulation results, the materials analyzed as potential target for neutron production are the following: ^{7}Li, ^{27}Al, ^{181}Ta, nat-Ag, ^{197}Au, ^{93}Nb. These are characterized by a limited and low energy range useful for the occurrence of the (p, n) reaction only. Since the cyclotron produces 18 MeV protons with fixed energy, in order to have less energetic beams, the incident energy must be appropriately degraded. For this reason, it is necessary to find a material that allows the degradation of the beam energy without producing unwanted neutrons. The best material has been found to be the graphite. In fact, unlike other materials which are characterized by several neutron producing reactions at the proton energy (18 MeV) it presents only the reaction (p, n + ^{3}He). The only problem in using ^{12}C is related to the high cross section (~ 6 barns) of the above mentioned reaction at the beam energy (Fig. 1). This implies that each acquired spectrum has a neutron background from the graphite that must be subtracted. Because of the three-body nature of this reaction, the only way to evaluate the contribution of graphite comes from simulations.

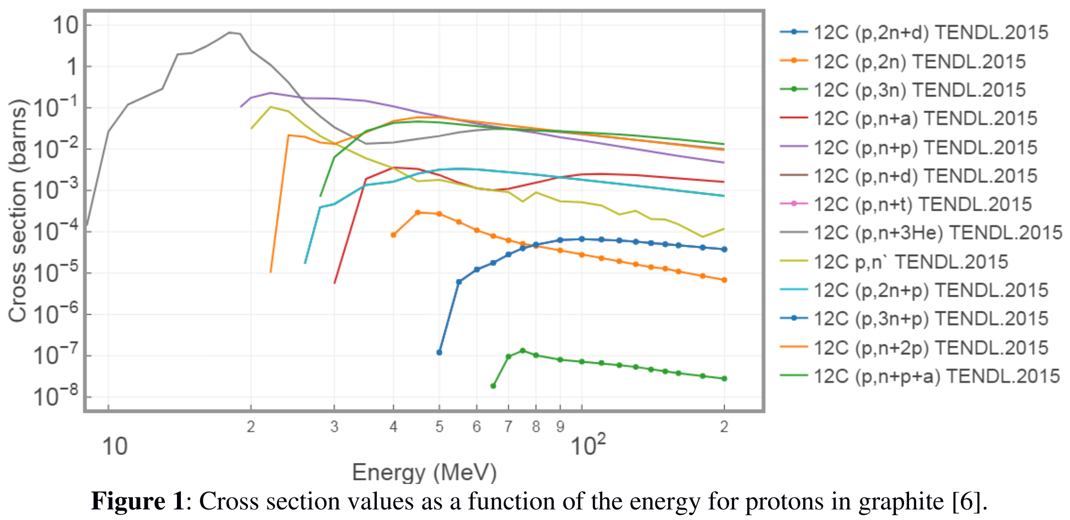

Figure 1: Cross section values as a function of the energy for protons in graphite [6].

3. Simulation results

In addition to the previous simulations, the design of the experiment was accomplished with the Monte Carlo simulation package FLUKA [7]. Simulations were carried out at first to evaluate the effectiveness of graphite.

As an example, in the Fig. 2a we show the neutron spectrum of an 18 MeV proton beam on a graphite target, and we compare it with the one in which a thin Lithium layer was added (Fig. 2b). As is evident, the presence of the Lithium layer, although very thin (50 µm), changes the shape of the spectrum: it behaves like a neutron moderator. The 4.5 MeV peak in fig. 2b refers to the neutrons produced in Lithium.

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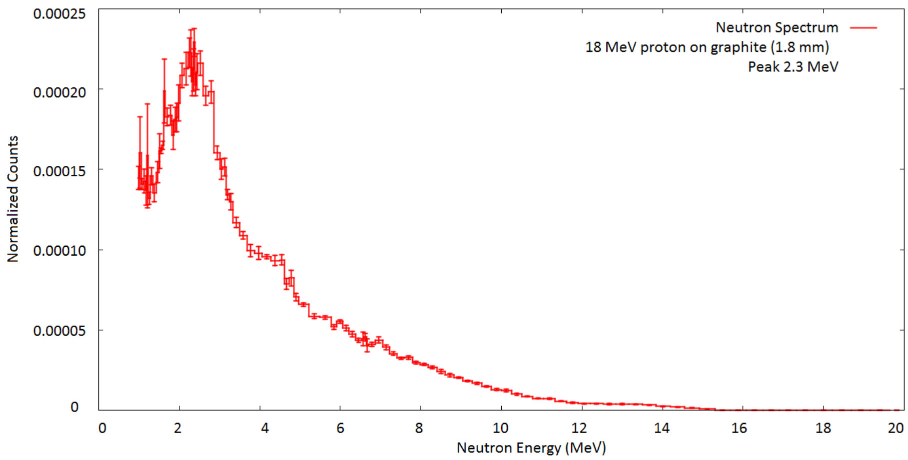
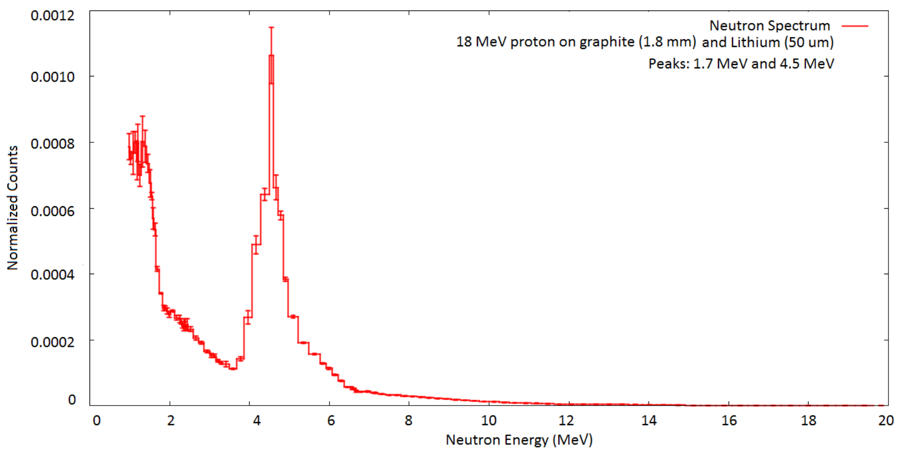
The same process is done with the other targets; then other elements were added, up to reach more complex configurations that better describe the geometry of our experiment.



a)



b)

Figure 2: Results of Fluka simulation for an 18 MeV proton beam on graphite layer (a) and a combination of graphite and Lithium (b).

4. The experiment

The neutron production was carried out for the first time at the IBA 18/9 Cyclone of the University of Bern LHEP. The 18/9 cyclotron is mainly used for the production of radioisotopes for nuclear medicine. It is equipped with a Beam Transport Line (BTL) on which there are many devices useful for the beam quality and focusing controls. A schematic of the main elements of the BTL is reported in Fig. 3.

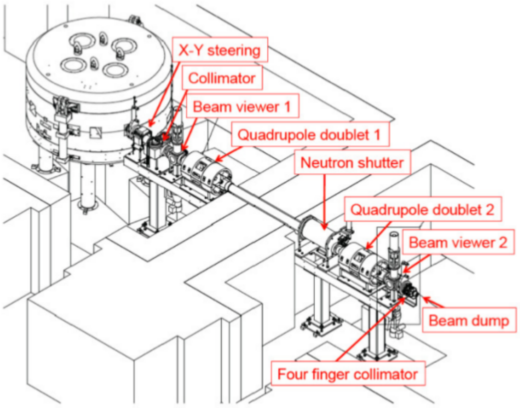
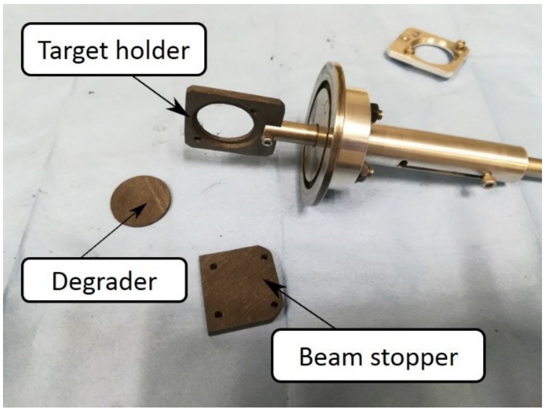


Figure 3: Schematic view of the Bern Cyclotron facility [8].

5. The target design

The target has been designed as shown in Fig. 4a): graphite degrader, target for neutron production and beam stopper (graphite). The second layer of graphite does not represent a problem in terms of neutron production, in fact at low energies there are no neutrons produced (Fig. 4b).

a)



b)

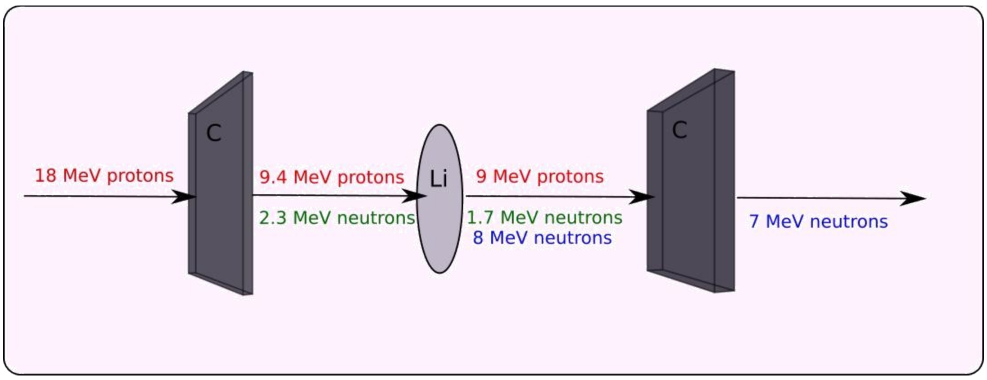


Figure 4: (a) Target designed for the experiment: target holder, beam stopper and degrader. (b) Scheme of the several processes which happen in each step of the multiple target.

6. The production

Measurements were made to produce neutron beams of different energies from different targets.

The detector used is the Berthold neutron dose-rate meter (Berthold LB 6411 probe) [9]. It is useful for measurements of the equivalent ambient dose for neutrons and consists of a moderating polyethylene sphere with a composite ^{3}He recoil proton counter tube, the LB 6410, at its center. The instrument has an extremely high sensitivity of approximately 3 counts/nSv, while the response for gamma radiation is approximately 10^3 counts/nSv.

The targets are positioned in the beam line as described above. The Berthold dosimeter is 80 cm far from the target and it is positioned at 0 degrees from the beam axis. The results of the measurements made with all the targets are compared with the analytical calculation (table 1) and shown in Fig. 5.

The intercept value different from zero corresponds to the neutrons produced in graphite. This is a background and a constant offset that has to be subtracted for all the measurements.

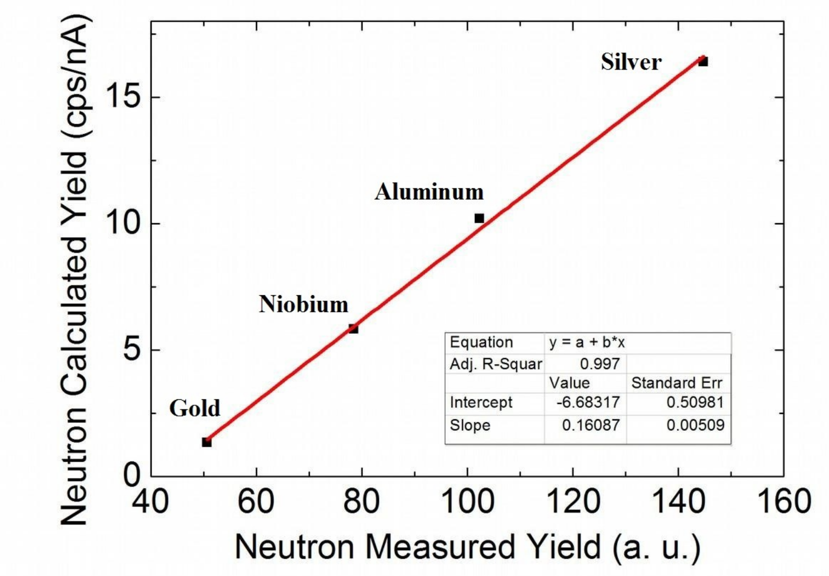


Figure 5: Linear fit (red line) between the calculated and the measured neutron yield for: Gold, Niobium, Aluminum and Silver. Data from the Table 1.

Target	Measured cps/nA	Calculated cps/nA
Nb	78.49 ± 1.16	5.83
Au	50.63 ± 0.80	1.35
Ag	144.74 ± 1.38	16.40
Al	102.30 ± 1.14	10.2

Table 1: Measured and calculated counts per second, normalized for the beam current (nA).

7. Conclusions

The measured neutron yields, normalized to the beam current, are in agreement with the analytical calculations, taking into account the contribution of neutrons produced in graphite.

This work opens interesting perspectives in the study of new methods for neutrons production and of their applications. First of all, the method investigated in this work, can be applied with intense proton beams, in order to reach neutron production rate up to 10^{10} pps. Improvements on the method could be obtained by

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optimizing the target design in order to use other kinds of target, including water cooled targets for high intensity beams.

Regarding the applications, this technique can be used in: cross section measurements for neutron production in different materials; setting up of a facility for testing of new generation detectors to be used in applied and fundamental Physics; use of neutron beams to produce radioisotopes in Medical Physics (^{99}Tc); design of a dedicated tunable neutron facility; use of high intensity proton beams for applications in many fields (Radiation Hardness).

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