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Beam of Monoenergetic Neutrons for the Calibration of a Dark-Matter Detector

A. N. Makarov and S. Yu. Taskaev

*Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences,
pr. Akademika Lavrent'eva 11, Novosibirsk, 630090 Russia*

e-mail: taskaev@inp.nsk.su

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A new method has been proposed for obtaining a beam of monoenergetic neutrons with almost arbitrary energies. The production of the beam for the calibration of a dark-matter detector with liquid argon as a working medium has been described.

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A number of experimental observations (rotation curves of galaxies [1], gravitational lenses [2], temperature fluctuations of cosmic microwave background [3], and abundance of light nuclei [4]) indicate the possible existence of dark matter, which constitutes the main mass of the Universe. Weakly interacting massive particles (WIMPs) are considered as most appropriate candidates for the explanation of all data [5]. They are nonrelativistic particles of the cold dark matter with masses near 10 GeV. They can be detected because the Earth moves with respect to the center of the Galaxy, whereas the cold dark matter is assumed to be at rest. A number of detectors have detected signals that can be attributed to the ionization of atoms of the detecting medium by WIMPs [6–9]. Since the Solar System rotates around the center of the Galaxy at a velocity of 220–250 km/s and the Earth rotates around the Sun at a velocity of 30 km/s, the momentum transfer is no more than several keV. To interpret the results, it is necessary to know the fraction of the total energy of recoil nuclei that is spent to ionization (quenching factor). It can be measured in the scattering of monoenergetic neutrons with an energy of tens of keV.

Monoenergetic neutron beams used in metrology cover the range of 2 keV to 390 MeV. The ^{7}Li(p, n)^{7}Be and ^{45}Sc(p, n)^{45}Ti reactions or a nuclear reactor with an iron filter is used in the low-energy region to obtain beams with energies of 2, 8, 24, 27, 70, and 144 keV [10–12].

In this work, we propose a method for the formation of a beam of monoenergetic neutrons with almost arbitrary energies. Its application for the calibration of a dark-matter detector with liquid argon as a working medium is described.

Neutrons are generated in the ^{7}Li(p, n)^{7}Be reaction induced by a proton beam with an energy higher than 1.882 MeV incident on a lithium target. This reaction is characterized by a fast increase in the cross section near the threshold, a relatively large cross section (0.3–0.6 b), and a relatively soft spectrum of generated neutrons (the average energy of neutrons is 75 keV for the 2-MeV proton beam). When a change in the energy of the monoenergetic neutron beam passing through the neutron-generating layer is small, the energy and emission angle of a neutron are unambiguously determined by kinematic relations. Figure 1 presents the relation of the energy of the neutron in the laboratory coordinate system to the polar emission angle for various energies of protons [13]. It can be seen that, when the energy of protons is above the reaction threshold, 1.882 MeV, but below 1.920 MeV, neutrons are emitted only into the forward hemisphere

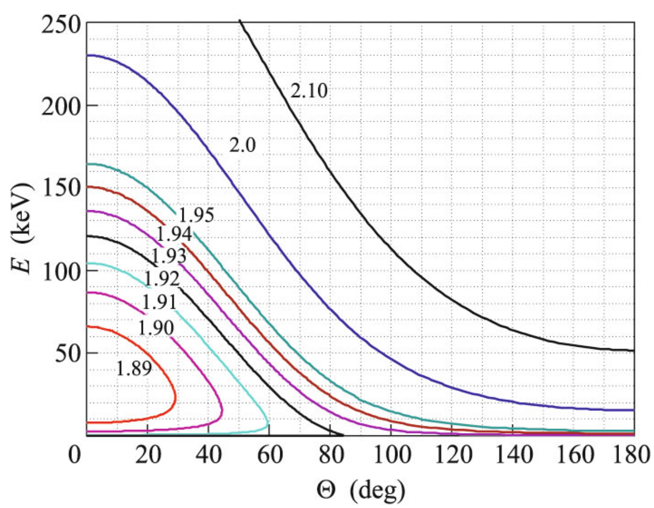

Fig. 1. Energy of the neutron E versus the emission angle Θ in the laboratory coordinate system for various energies of protons presented in MeV near the corresponding curves. The angle is measured from the direction of the proton beam.

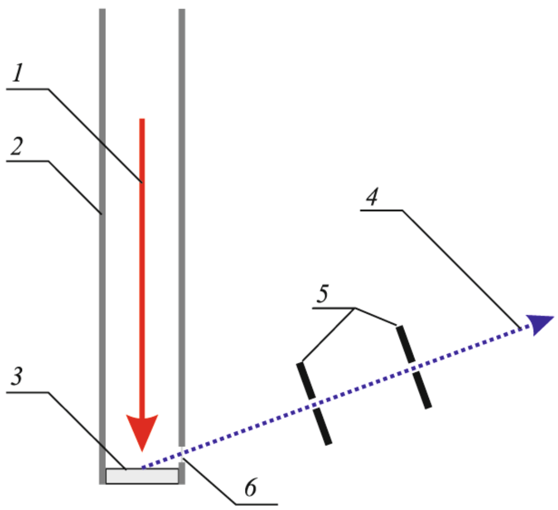

Fig. 2. Setup for obtaining a beam of monoenergetic neutrons: (*1*) neutron beam, (*2*) vacuum chamber, (*3*) neutron-generating target, (*4*) beam of monoenergetic neutrons, (*5*) collimator, and (*6*) window.

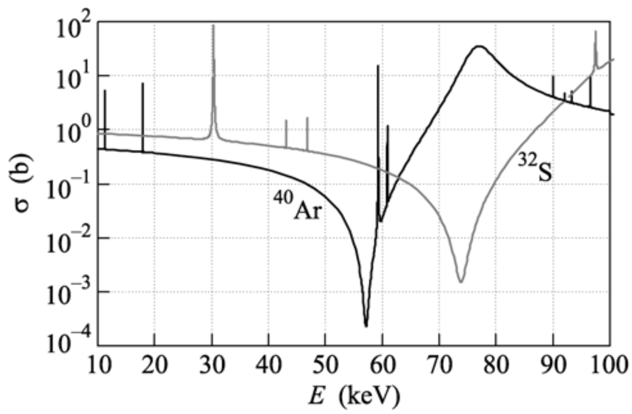

Fig. 3. Cross section for the elastic scattering of the neutron by ^{40}Ar and ^{32}S according to ENDF/B-VII.1 database.

and are characterized by two monoenergetic lines. When the energy of protons is higher than 1.920 MeV, neutrons are emitted in all directions and are characterized by only one monoenergetic line. According to Fig. 1, monoenergetic neutron beams with any energy can be created by varying the energy of protons and observation angle larger than 90°. Backward emitted neutrons do not pass through the cooled substrate of the lithium target, which is minimized in thickness, but inevitably leads to the scattering and deformation of the spectrum. The energy of these neutrons depends only slightly on the angle and the energy of protons. This makes it possible to ensure high monochromaticity.

The monochromaticity of emitted neutrons is determined by the thickness of the lithium layer, because protons are decelerated when passing through this layer and the energy of emitted neutrons decreases. In particular, the energy of the proton after passage of 1 μm of the lithium layer decreases by 3.1 keV from an initial value of 2 MeV [14] and the energy of neutrons emitted at an angle of 110° decreases by 1.5 keV. Thus, the energy distribution of neutrons after passage through the 1-μm lithium layer is broadened by 2%. Monochromaticity depends also on the solid angle: a 1° variation in the angle at a proton energy of 2 MeV and an emission angle of 110° leads to a change in the energy of neutrons by 1.4 keV, i.e., to the same 2% broadening.

The proposed method for the formation of the monoenergetic neutron beam can be implemented with an accelerator source of epithermal neutrons that was created for the development of the method of boron–neutron capture therapy of malignant tumors [15]. Figure 2 shows the beam production layout. Monoenergetic protons *1* with an energy above 1.920 MeV propagating in vacuum chamber *2* are incident on target *3*. The target consists of a cooled substrate coated by a thin lithium layer on the side irradiated by the proton beam [16]. The interaction of protons with lithium nuclei leads to the emission of neutrons in all directions. Backward emitted neutrons (with respect to the direction of motion of protons) are used to form monoenergetic neutrons *4* by collimator *5*.

This method can provide monoenergetic neutrons with almost any energy. According to Fig. 3, the maximum efficiency of the scattering by argon nuclei (working medium of the detector) is reached for 77-keV neutrons, which are obtained at an emission angle of 110° with a 2.070-MeV proton beam. For additional monochromatization of the neutron beam, a sulfur filter can be used because it is transparent to neutrons with the given energies, as can be seen in Fig. 3, where the energy dependence of the cross section for scattering of neutrons by ^{32}S is shown.

A target with the lithium layer about 50 μm in thickness is used in the accelerator source of epithermal neutrons [17]. This source generates neutrons for in vitro studies. The energy spectrum of neutrons emitted at an angle of 0° covers the entire range up to 100 keV and has a maximum in the range of 40–80 keV [18]. Two-thirds of scattering events in the argon detector irradiated by such a neutron beam are due to neutrons with energies from 60 to 80 keV; this circumstance can be used for preliminary calibration.

To generate monoenergetic neutrons, the blinking source scheme, i.e., generation of neutron pulses, which allows synchronization and time-of-flight measurement of the energy of neutrons, can be useful. The generation of neutron pulses with a stationary proton beam is performed as follows [19]. The energy of the proton beam is below the 1.882-MeV threshold of the ^{7}Li(p, n)^{7}Be reaction; consequently, neutrons are not generated. However, a negative voltage pulse of 50 kV with a duration of 200 ns supplied to the neutron-generating target, which is electrically insulated from the case of the setup, increases the energy of protons and leads to the generation of neutron pulses.

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