Simulation study of interaction of neutrons with CsI crystal for dark matter search

S. Seth[1,*] S. Batabyal[2], P. Bhattacharjee[1,3], S. Bhattacharya[1,3], D. Das[1,3], M. Das[1,3], C. C. Dey[1,3], S. Ghosh[1,3], Meghna. K. K.[4], B. Karmakar[1,3], D. Majumdar[1,3], P. Majumdar[1,3], N. K. Mondal[1], S. Saha[1,3], and M. K. Sharan[1,3]
[1] *Saha Institute of Nuclear Physics, Kolkata 700 064 , INDIA*
[2] *University of Delhi, New Delhi 110 021, INDIA*
[3] *Homi Bhabha National Institute, Anushaktinagar, Mumbai 400 094, INDIA and*
[4] *National Institute of Science Education and Research, Jatni 752 050, INDIA*

Introduction

Weakly Interacting Massive Particles (WIMPs) are one of the most promising cold dark matter (CDM) candidates. Direct detection experiments for dark matter (DM) search look for signatures of nuclear recoils produced due to WIMP-nucleus elastic scattering. The Mini-DINO experiment, the first phase of the proposed DM search experiment in India, namely, the"DINO" experiment, proposes to use suitable scintillation crystal detectors operated at cryogenic temperatures for the detection of scintillation light due to possible WIMP induced recoiling nuclei. Since neutrons can also give rise to nuclear recoils similar to WIMPs, a good idea of the expected response of the detector to WIMPs can be obtained by studying the detector's response to neutrons from a neutron source or a mono-energetic neutron beam at the laboratory.

It is a common practice to calibrate the scintillation light output of the scintillators with standard gamma ray or electron sources. For recoiling nuclei, only a fraction, called the Quenching Factor (QF), of the total recoil energy, $E_{\rm recoil}$, of the nucleus goes to produce the scintillation light output, the rest going into other forms such as lattice vibrations (phonons). The quenching factor can be expressed as, $\mathrm{QF} = \frac{\mathrm{L_{recoil}}}{\mathrm{E_{recoil}}}\frac{\mathrm{E_{\gamma,calib}}}{\mathrm{L_{\gamma,calib}}}$ where $\mathrm{L_{\gamma,calib}}$ is the measured light output due to γ-rays of known energy $\mathrm{E_{\gamma,calib}}$ from a calibration source, and $L_{\rm recoil}$ is the measured light output due to the recoil nucleus of energy $E_{\rm recoil}$. Some recent studies towards determination of the quenching factors for neutron-induced Caesium (Cs) and Iodine (I) recoil nuclei within CsI crystal can be found, e.g., in Refs. [1–3].

In the present study, attempts are made to understand the scintillation characteristics of nuclear recoil events in scintillation crystals for possible application in DM search experiments. The nature of the recoil energy distribution of neutron-induced recoiling Cs/I nuclei is studied using the GEANT4.10.02 simulation toolkit [4] and the behaviour of the quenching factor of the Cs/I nuclei in CsI crystal as a function of the recoiling nucleus energy is studied using the SRIM software [5].

Present Work

In the present work, we have studied the interaction of neutrons with CsI scintillation crystal to simulate the energy distribution of the recoiling nuclei using GEANT4.10.2. In the simulation, a cylindrical CsI crystal of diameter 2.2 cm and height 4.0 cm is considered. The crystal is placed within a 4 mm thick copper cylinder, which is kept at the center of a 2 m × 2 m × 2 m room made of 24 cm thick concrete walls all around. In the simulation, a mono-energetic neutron beam of energy 14.1 MeV is incident on the CsI crystal from a distance of 50 cm from the crystal face and traverses in the direction of the long axis of the crystal. The energy distributions of the recoiling Cs and I nuclei are obtained from

*Electronic address: susnata.seth@saha.ac.in

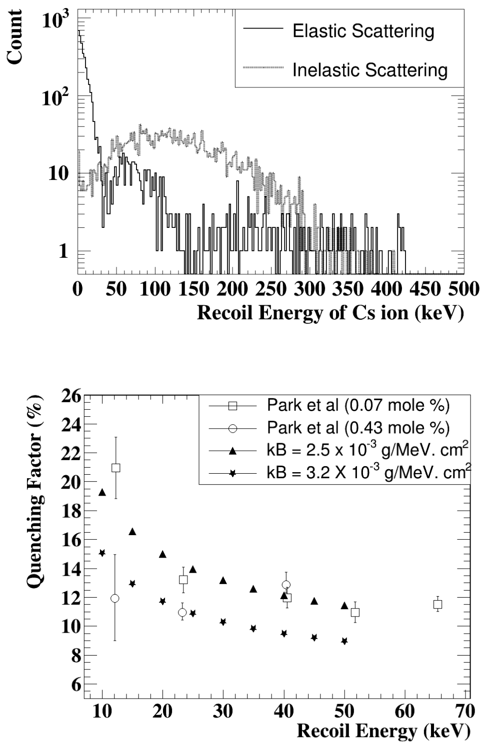

FIG. 1: (top) Distribution of recoil energy of Cs nuclei from single elastic and single inelastic scattering events of neutrons and (bottom) Cs quenching factors as a function of recoil energy obtained from Birks's formula (see text) with the stopping power dE/dx calculated using SRIM and with two different values of the Birks factor kB= 2.5×10^{-3} g/(MeV.cm^2) (filled triangles) and kB=3.2×10^{-3} g/(MeV.cm^2) (filled star). For comparison, the experimental data from Ref. [1] are also shown for two different Tl doping concentration in CsI(Tl).

the GEANT4 simulation results. The stopping powers of the recoiling Cs and I nuclei as functions of their recoil energy are obtained separately using the SRIM code.

Results and Discussions

The GEANT4 simulation shows that neutrons interact with the detector nuclei both through elastic as well as inelastic scattering. The distribution of recoil energy of Cs nuclei generated from elastic and inelastic scattering events of neutrons are shown in Fig. 1 (top). The quenching factors for recoiling Cs nuclei of different energies in CsI crystal are calculated using the equation (based on Birks's Formula) [2],

$$\mathrm{QF} \simeq \frac{1}{\mathrm{kB(dE/dx)}}, \tag{1}$$

where kB is the so-called "Birks factor" and dE/dx is the stopping power of the Cs nucleus. For a given crystal, this equation depends only on one unknown parameter, namely, the Birks factor (kB), which can be determined by fitting the calculated value of the quenching factor for various values of this parameter to the experimental data for a given particle. The value of kB so determined can then be used for determining the quenching factors for other nuclei in the same crystal as well.

In Fig. 1 (bottom), it is observed from experimental data [1] that the quenching factors vary with the concentration of Tl doping within the CsI(Tl) crystal. Our values of kB, that bracket well the range of experimental values of QF for the two Tl doping concentrations considered, are found to be in reasonable agreement with — albeit somewhat lower than — the values of this parameter quoted, e.g., in Ref. [3].

References

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