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Nuclear-recoil energy scale in CDMS II silicon dark-matter detectors

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ABSTRACT

The Cryogenic Dark Matter Search (CDMS II) experiment aims to detect dark matter particles that elastically scatter from nuclei in semiconductor detectors. The resulting nuclear-recoil energy depositions are detected by ionization and phonon sensors. Neutrons produce a similar spectrum of low-energy nuclear recoils in such detectors, while most other backgrounds produce electron recoils. The absolute energy scale for nuclear recoils is necessary to interpret results correctly. The energy scale can be determined in CDMS II silicon detectors using neutrons incident from a broad-spectrum ^{252}Cf source, taking advantage of a prominent resonance in the neutron elastic scattering cross section of silicon at a recoil (neutron) energy near 20 (182) keV. Results indicate that the phonon collection efficiency for nuclear recoils is $4.8^{+0.7}_{-0.9}\%$ lower than for electron recoils of the same energy. Comparisons of the ionization signals for nuclear recoils to those measured previously by other groups at higher electric fields indicate that the ionization collection efficiency for CDMS II silicon detectors operated at ∼4 V/cm is consistent with 100% for nuclear recoils below 20 keV and gradually decreases for larger energies to ∼75% at 100 keV. The impact of these measurements on previously published CDMS II silicon results is small.

1. Introduction

Strong evidence indicates that ≳80% of the matter in the Universe is non-luminous and non-baryonic [1]. Weakly Interacting Massive Particles (WIMPs) are a leading class of theoretically motivated candidates for this dark matter [2]. These particles are expected to interact with normal matter through the weak nuclear force and to cluster gravitationally. If WIMPs do constitute our galaxy's dark matter, they may be detectable through their elastic scattering off atomic nuclei in terrestrial detectors [3]. Under standard galactic halo assumptions [4] for a WIMP mass of $\sim 100\,\mathrm{GeV}/c^2$, the recoiling nuclei have energies of tens of keV and ranges of 10–100 nm in solid matter.

The Cryogenic Dark Matter Search (CDMS II) experiment measured nuclear recoils using a target mass composed of high-purity silicon and germanium semiconductor crystals operated at ∼50 mK. Each crystal was instrumented to simultaneously measure the electron–hole pairs (ionization) and athermal phonons created by particle interactions within the crystal [5].

A WIMP, or a neutron, may scatter off a nucleus producing a nuclear recoil (NR), while most other interactions produce an electron recoil (ER). Accurate determination of an event's energy requires a systematic calibration of the recoil energy scale. This energy calibration is generally straightforward for electron recoils due to the availability of a variety of spectral lines from radioactive sources over a wide range of energies.

The calibration for nuclear recoils is more difficult. CDMS II used a ^{252}Cf neutron source to perform nuclear-recoil calibrations, and the spectrum of recoil energies in CDMS II detectors resulting from exposure to this source decreases quasi-exponentially with increasing energy and is nearly featureless. For CDMS II detectors, knowledge of the nuclear-recoil energy scale to within ∼10% is sufficient to accurately interpret WIMP-search results for WIMP masses greater than a few tens of GeV/c^2. For lower masses, however, a more accurate determination of the energy scale is important for a robust comparison of results from different experiments, particularly in light of interpretations of data from several experiments as possible evidence for a low-mass ($<10\,\mathrm{GeV}/c^2$) WIMP [6–9].

This paper describes the procedure used to calibrate the nuclear recoil response of CDMS II silicon detectors. Experimental data for this study are drawn from the final runs of these detectors at the Soudan Underground Laboratory, from July 2007 to September 2008, as described in Ref. [9]. *In situ* measurements of elastic neutron scatters in these detectors from a ^{252}Cf source are compared to Monte Carlo simulations of recoiling nuclei in the detectors. A re-calibrated energy scale is derived, optimizing agreement between measured and simulated recoil spectra. This is used to adjust the published upper limits on the WIMP-nucleon spin-independent cross section, as well as the 90% C.L. acceptance region from the analysis of the final exposure of the silicon detectors [9].

2. CDMS II detectors

The final configuration of CDMS II contained 11 silicon and 19 germanium Z-sensitive Ionization- and Phonon-mediated (ZIP) detectors. These were arrayed into five "towers", each containing six detectors following the designation TxZy where x (1–5) is the tower number and y (1–6) indicates the position within the stack (from top to bottom). We focus here on the silicon detectors used in Ref. [9], which were ∼10 mm thick, 76 mm in diameter, with a mass of ∼106 g each. Of the eleven silicon detectors, two were excluded due to wiring failures leading to incomplete ionization collection, and a third was excluded due to unstable phonon channel response.

Each detector was photolithographically patterned with sensors on both flat faces: two concentric ionization electrodes on one face and four independent phonon sensors on the opposite face. The ionization electrodes were biased to 4 V with respect to the phonon electrodes, creating an electric field of 4 V/cm in the bulk of the detector along its z axis [10]. The electrons and holes generated by a particle interaction were separated and drifted across the crystal by the electric field, generating image currents in the electrodes detected by a JFET-based charge amplifier [11]. By careful neutralization of ionized trapping sites within the crystal with regular exposure to infrared LEDs ("flashing"), the detectors were operated in a metastable state in which trapping of charge carriers in the crystal bulk was low. The ionization collection efficiency for electron recoils was therefore high, despite the relatively modest applied electric field.

In semiconductor devices such as the ZIPs, phonon (φ) energy is generated by three interactions: the initial recoil generates primary phonons, the work done on the charge carriers by the electric field generates Neganov–Trofimov–Luke (or NTL) phonons [12–14], and charge carrier relaxation to the Fermi level at the electrodes generates