Measurement of low-energy Compton and neutron scattering in Si CCDs for dark matter searches

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Abstract

For optimal sensitivity to low-mass dark matter candidates experiments like DAMIC-M employ skipper charged-coupled devices (CCDs) with detection threshold of just a few ionization charges. Ionization signals from small-angle Compton scatters of environmental γ-rays, an important component of the background in dark matter searches, must thus be characterized down to $O(10\,\text{eV})$ energy. Using a ^{241}Am γ-ray source, we report a precise measurement of scattering on Si atomic shell electrons in a skipper CCD with single-electron resolution. Notable differences are observed between data and theoretical expectations in the L-shell energy region (<150 eV). We also present preliminary data from a skipper CCD exposed to low-energy neutrons (<24 keV) from a ^{124}Sb^{9}Be photoneutron source, demonstrating a measurement of the nuclear recoil ionization efficiency in Si down to few ionization charges.

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1 Introduction

The DAMIC-M (Dark Matter in CCDs at Modane) experiment [1] will search for dark matter particles by measuring nuclear and electronic recoils in the Si bulk of charge-coupled devices (CCDs). The CCDs will measure charge with sub-electron resolution and will be assembled in an ultra-low background environment. Thanks to these improvements, DAMIC-M can reach the required sensitivity to search for low-mass ($1-10^4$ MeV/c^2) dark matter candidates. For additional information on DAMIC-M, you can check contributions by D. Norcini and A. Chavarria in this proceeding.

A prominent background in ultra-low background dark matter detectors are energy deposits by high energy γ-rays, which can originate in the detector and shielding materials.

Compton scattering of these γ-rays produces point-like energy deposits uniformly distributed in the Si bulk, similar to dark matter particles interactions. Low-energy electrons produced by γ-rays are a challenge for background models and have not been experimentally validated at low energies. These events deep in the active detector volume can not be easily rejected like surface events from low-energy β sources. In addition, understanding of scattering on electrons bound in semiconductors is relevant also for DM-electron scattering. A precise measurement of the L-shell step of the Compton spectrum will provide calibrations of the detector response down to a few electrons and hence, improving sensitivity for low-mass dark matter searches.

Our second measurement aims to characterize nuclear recoil ionization efficiency of neutrons elastically scattering off Si nuclei, which is relevant for the detection of low-mass (<10 GeV/c^2) weakly interacting massive particles (WIMPs). Theoretical models that predict the nuclear recoil ionization efficiency in Si are highly uncertain in this low-energy regime and dedicated calibrations are required.

A campaign of the two calibration measurements is under way at The University of Chicago with the help of the DAMIC-M collaboration. The goal is to provide precise detector calibration at low energy threshold of E_{th}=23 eV, corresponding to $\sim$6 e$^-$. In this way, we can improve on previous results obtained with standard CCDs and the energy threshold of E_{th}=60 eV [2, 3]. The results of our Compton measurement has been already submitted to a journal, see [4].

2 Experimental setup and skipper CCDs

The experimental setup is located in an on-surface clean room at the University of Chicago. The configuration used for the Compton measurement is shown in Fig. 1 and very similar setup is used also for the photoneutron measurement. A CCD is mounted in a copper frame inside a stainless steel vacuum chamber. Aluminium plates of 1.6 mm thickness cover the CCD from both sides to blocks infrared radiation emitted by the chamber itself. The CCD is cooled down to about 130 K and kept in vacuum during the data taking. The CCD is controlled with a chain of commercial and custom-made electronics.

For the Compton measurement, a ^{241}Am source was positioned directly on the back flange of the vacuum chamber, centered on the CCD plane. To allow only γ-rays with energy E_γ=59.5 keV from the ^{241}Am source, a 13 mm aluminium plate blocks γ-rays emitted at lower energies. In the case of the photoneutron measurement, a ^{124}Sb^{9}Be source sits in a lead castle on a trolley parked in front of the chamber.

A skipper CCD with 1024×6176 pixels is used as the Si target and detector in both measurements. It features a buried p-channel, pixel size of 15×15 μm^2 and high-resistivity (10–20 kΩ cm) n-type Si with a thickness of 670 μm. The Si bulk can be fully depleted operation at substrate biases $\geq$40 V. The CCD was developed at Lawrence Berkeley National Laboratory MicroSystems Lab [5–7] and fabricated by Teledyne DALSA Semiconductor as a prototype for the DAMIC-M experiment. Wirebonding and packaging was completed at the University of Washington.

Unlike conventional CCDs, skipper CCDs [8–10] can be configured to make multiple non-destructive charge measurements (NDCMs) or skips. The readout noise is then reduced to $\sigma_{N_{skip}} = \sigma_1/\sqrt{N_{skip}}$, where σ_1 is the single-sample readout noise (the standard deviation of a single charge measurement) and N_{skip} is the number of NDCMs. By taking a large enough number of NCDMs, the readout noise can reach the sub-electron level and the detection threshold is reduced accordingly.

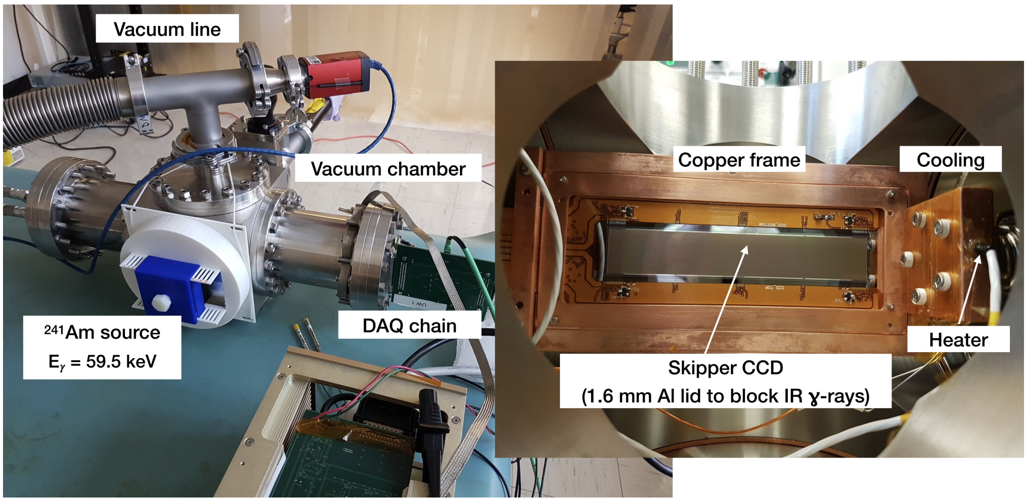

Figure 1: Experimental setup during the Compton data taking. The blue box fixed on the flange of the vacuum chamber contains the ^{241}Am source with Al plate blocking low energy γ-rays.

3 Data taking, calibration and simulations

CCD operational parameters had been optimized before two data taking runs to (1) collect enough statistics for an accurate measurement at low energy within half a year, (2) have sufficient single electron resolution, (3) avoid overlapping clusters from a source which may distort the energy spectrum. Good data taking conditions for the Compton measurement were achieved with $N_{skip} = 64$ providing resolution σ_e=0.73 e$^-$ and binned images, where the binning sums the charge of 4×4 pixels (columns × rows) before the charge readout. This combination and further analysis lead to the energy threshold E_{th}=23 eV (∼6 e$^-$).

The data set collected for the Compton measurement includes the total exposure of 105.5 days with the ^{241}Am source, 48.1 days for the background set (i.e. without the source) and 11.8 days of images when only a serial register was read (i.e. clocking only the charge in the serial register towards the CCD readout amplifier) while keeping the ^{241}Am source installed. The last data set is important for the correct background subtraction at very low energies. For monitoring purposes, we periodically took full CCD images with no binning to check defects (faulty pixels) in the CCD. Images with N_{skip}=2000 (i.e. σ_e=0.13 e$^-$) and 16×4 binning were used for precise calibration and checks of dark current.

Single electron resolution provides a powerful and simple way to calibrate the pixel charge measured in ADU. We use high resolution data (N_{skip}=2000) and calculate the charge (and also resolution) using only 64 of the 2000 skips with a Gaussian fit for each peak. Over 550 consecutive electron peaks ($E \approx$ 2.1 keV) are individually resolved with sufficient statistical precision and show that our calibration and charge resolution are stable within few percents up to the K shell energy and above for N_{skip}=64. Ongoing data taking for the photoneutron measurement follows very similar approach.

A full simulation of the experiment setup, including an accurate description of the geometry and materials of the the chamber and used source, have been developed with GEANT4 simulation toolkit [11].

To validate the data analysis methods, determine the reconstruction efficiency and interpret the results we have generated set of realistic images. First, the deposited energy of γ-rays in the CCD simulated with GEANT4 is converted to the number of electrons by either sampling electron-hole pair creation probabilities [12] if E_{dep}<50 eV or the average electron-hole pair creation energy ($\epsilon_{eh} = 3.74\,\mathrm{eV/e^-}$) with Fano factor (F=0.128) for higher energies. Electrons are then diffused in the bulk Si towards the pixel array, charges are assigned to pixels and the simulated events are pasted onto images from the background data set to properly include the pixel readout noise, the dark current, and the presence of cosmic rays and other tracks. These simulated images are processed with the same cluster reconstruction and analysis chain as the data. The reconstruction efficiency is 100% for energy deposits as low as 15 eV and we accurately reconstruct the expected features at the lowest energy of the simulated Compton spectrum.

4 Measured Compton spectrum

Our measured Compton spectrum from scatter of 59.5 keV γ-rays in Si above the energy threshold of 23 eV is shown in Fig. 2. We clearly identify features associated with the L_1 (150 eV) and $L_{2,3}$ (99.2 eV) shells (see the inset). For the first time, we detect a plateau below the $L_{2,3}$ energy (99.2 eV) corresponding to Compton scattering only on valence electrons. Let us note that in a recently reported measurement also with a skipper CCD [13] this expectation was not verified, due to the presence of unsubtracted backgrounds.

Two models are shown in the figure: the GEANT4 simulated spectrum (purple) that is based on the relativistic impulse approximation (RIA) [14] and the ab initio calculation from the FEFF code [15,16] (red), which is a self-consistent calculation of local electronic structure and X-ray absorption spectra originally developed for X-ray absorption spectroscopy. Both models are in agreement with the data above 0.5 keV and one can see that the K-shell step at 1.8 keV is observed and accurately reproduced by the Monte Carlo simulation.

There is an excellent agreement with the data over the entire energy range. In particular, FEFF reproduces L-shell features to better than 10% , where a softening of the spectrum and step is observed. While the RIA model fails to reproduce a softening of the observed spectrum and overestimate rates by up to 20% in the L-shell region, confirming the previous measurement [2]. For more details see [4].

5 Photoneutron measurement

A measurement of nuclear recoil ionization efficiency in Si is currently taking place with modified setup described above. We use 24 keV neutrons from a ^{124}Sb^{9}Be source placed inside a lead shielding to attenuate high energy γ-rays. Photonuclear interactions between 1691 keV γ-rays from ^{124}Sb decay and ^{9}Be result in almost monochromatic neutrons of 24 keV. Materials between the source and the CCD moderate the original neutron flux and therefore, the energy spectrum of neutrons reaching the CCD must be properly simulated.

Our preliminary energy spectrum measured with $N_{skip} = 400$, giving σ_e=0.30 e$^-$, was presented at this conference and it has similar shape as the one published in [3]. To explore even lower energy region, we have started taking higher resolution data with $N_{skip} = 1600$ or σ_e=0.15 e$^-$.

The next steps are the calibration the neutron flux with a ^{3}He counter and development of simulations of the source and experimental setup. We will extract the ionization efficiency of neutrons in Si and check, if it deviates from the extrapolation of the Lindhard model to low energies as measured in [3].

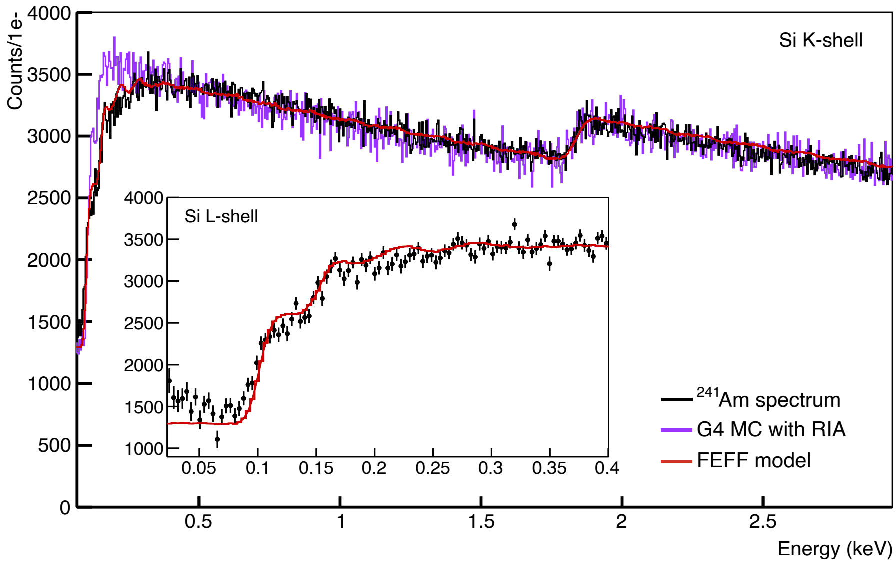

Figure 2: The measured ^{241}Am Compton spectrum (black) from the 23 eV detection threshold to 2.1 keV. The K-step is observed at 1.8 keV. The GEANT4 simulated spectrum (purple) that is based on the relativistic impulse approximation and the FEFF calculation (red) are also shown. The inset shows the data comparison to the FEFF prediction in the L-shell energy range.

6 Conclusions

Two calibration measurements in Si performed with a DAMIC-M prototype CCD were presented at this conference. The Compton measurement significantly improvement on previous results both in terms of resolution and threshold. We found that the measured spectrum at low energies can be described with the FEFF code, while commonly used GEANT4 RIA simulations fail to reproduce the spectrum. Since RIA-based simulations are used to build background models for direct detection experiments, care should be taken to evaluate their impact on the sensitivity to a potential dark matter signal. The measurement of nuclear recoils with neutrons is taking progress and only preliminary results were presented here.

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