Large-Area, Low-Cost Si(Li) Detectors for Cosmic Particle and Nuclear Physics

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Over the past decade, a lithium-drifted silicon (Si(Li)) detector fabrication technique has been developed to satisfy the large-area, low-cost, and relatively high-temperature (-35 to -45 C) requirements of the GAPS (General Antiparticle Spectrometer) Antarctic balloon experiment[1–6]. In this letter, we summarize this novel detector design and its performance for both X-ray spectrometry and tracking, and outline how further optimization of these Si(Li) fabrication techniques will enable breakthroughs in sensitivity to rare cosmic signatures of dark matter and identification of rare heavy nuclei at accelerator facilities.

Current progress: The GAPS Si(Li) detectors GAPS is the first experiment optimized specifically for detection of low-energy ($E < 0.25$ GeV/n) cosmic antiprotons, antideuterons, and antihelium as signatures of dark matter annihilation or decay, probing dark matter models over a wide mass range that cannot be resolved with other search methods[7;8]. To achieve sensitivity to cosmic antinuclei in this unexplored low-energy range, GAPS uses a novel particle identification method based on exotic atom capture and decay[9–11]. First, the low-energy incident cosmic-ray antiparticle is trapped by the target Si and forms an exotic atom. The signature of characteristic de-excitation X-ray energies and nuclear annihilation decay product multiplicity, along with the incident dE/dx losses and stopping depth within the instrument, is then used to distinguish different antiparticle species.

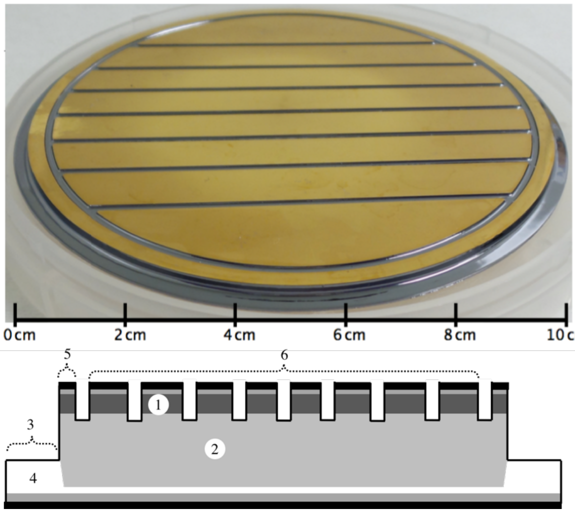

Figure 1: *Top*: 10 cm-diameter, 2.5-mm thick GAPS Si(Li) detector. *Bottom*: Cross-section (not to scale). Li ions from the n+ Li-diffused layer (1) are drifted through the p-type wafer to form an active volume (2). The 3 mm-wide top-hat brim (3) and a 0.1 mm-thick p-side remain undrifted (4). The 1 mm-wide grooves separate the guard ring (5) and the eight readout strips (6).

The heart of the GAPS instrument is ten planes of 1440 10 cm-diameter, 2.5 mm-thick, 8-strip Si(Li) detectors (Fig. 1), surrounded on all sides by a plastic scintillator time-of-flight system. The Si(Li) detectors must provide the active area ($> 10\,\mathrm{m}^2$), energy resolution (< 4 keV FWHM), stopping power, and particle tracking capability necessary for this identification technique, all within the significant temperature, power, and cost limitations of an Antarctic long-duration balloon mission. Using on-campus facilities, we first established the techniques necessary to produce large-area Si(Li) detectors for an order of magnitude lower cost than previous commercially-available detectors[1]. In partnership with Shimadzu Corp. we then adapted our large-area techniques to commercial-scale production[2–4], and validated the flight detector design[5;6] (Fig. 2). Over 1000 Si(Li) detectors have already been produced for the initial GAPS flight, scheduled for late 2022. GAPS anticipates at least three Antarctic balloon flights in the coming decade.

Future development: Improved Si(Li) designs for next-generation instruments By eliminating the magnets necessary for AMS and BESS, the GAPS exotic atom technique has already enabled larger acceptance. The low-cost Si(Li) production method is a key step in this, as it speeds turnover for subsequent flights and allows for the largest possible instrument area. Continued development opens the door to next-generation balloon and space-based missions to drastically improve sensitivity to rare cosmic signatures, and even measure spectra of any discovered signal with high statistics.

To further improve sensitivity to rare cosmic antinuclei, continued detector development is key, including increasing detector packing efficiency and reducing dead area, and exploring varying detector thicknesses. To reduce dead area, the simplest approach is to completely remove the top-hat brim after drifting and reduce the guard ring. In addition, square or hexagonal geometries would allow for greater packing efficiency. These can be machined out of the circular Si wafers; due to the low cost of our custom SUMCO Si (~\$100 per wafer), the cost of this wasted material is minimal. The second approach is to replace ultrasonic impact grinding (UIG) with deep reactive ion etching to produce groove as narrow as $\mathcal{O}(10\,\mu\text{m})$ and a guard ring $\mathcal{O}(100\,\mu\text{m})$ wide. In addition, varied thicknesses would allow for investigation of flexible future design options, such as expanding the sensitive energy range, allowing for overlap with the AMS-02 energy range and paving the way for spectral measurements of any discovered antideuteron signal. Thicker detectors would also be ideal for use at rare isotope facilities, as discussed below.

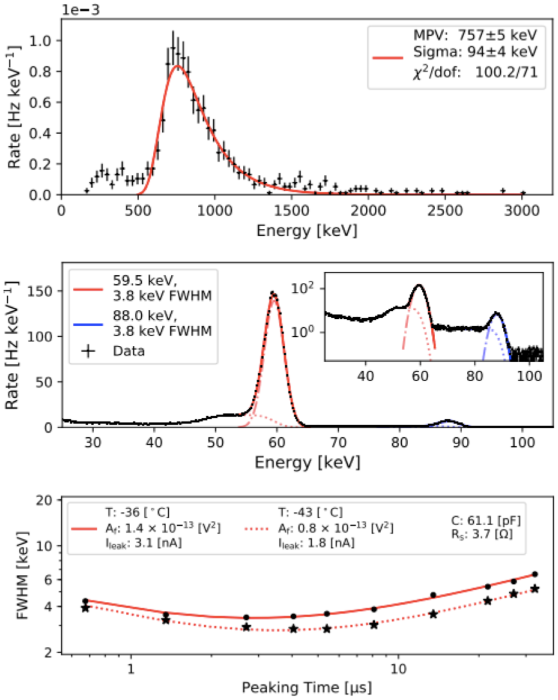

Figure 2: Performance of the GAPS Si(Li) detectors for X-ray spectrometry and particle tracking[5]. *Top:* Spectrum of cosmic muons. *Middle:* X-ray energy resolution measured using ^{241}Am and ^{109}Cd, with fits to the photopeaks and Compton scattered components. *Bottom:* Resolution varies with pulse peaking time and temperature according to the standard noise model for semiconducting Si.

Future development: Custom detectors for nuclear physics Continued Si(Li) detector development will enable broader applications of this novel technology, specifically a custom detector for nuclear physics' new flagship Facility for Rare Isotope Beams (FRIB). FRIB is a next-generation accelerator, scheduled to come online in 2022, that will allow scientists to study properties of rare isotopes in order to better understand the physics of nuclei, nuclear astrophysics, fundamental interactions, and applications for society[12].

These Si(Li) detectors are proposed to replace the hodoscope calorimeter in the S800 magnetic spectrometer at NSCL/FRIB, and potentially at the High Rigidity Spectrometer at FRIB[13;14]. In these experiments, an isotope beam is scattered off of a target, and the resulting exotic nucleus is measured. Two drift-chamber tracking detectors provide time-of-flight and trajectory measurements, an ion chamber provides ΔE, and a scintillator provides timing signal and event trigger. Planes of Si(Li) detectors would be placed at the end this suite of detectors to provide a measurement of total kinetic energy. In combination with the mass-to-charge ratio (derived from magnetic rigidity and time-of-flight) and atomic number (derived from ΔE), this allows for independent identification of both the charge and mass number.

Specifically, these Si(Li) detectors will aid in identification of fast heavy nuclei (~100 MeV/u). The current hodoscope uses Cs(I) crystals; competing designs that used stacks of Si detectors were previously too expensive to implement. The GAPS Si(Li) fabrication now makes it cost effective to cover the large focal plane ($>60\,\text{cm} \times 30\,\text{cm}$). This enables a hodoscope design with superior energy resolution, which is key to charge-state separation for $Z > 50$ nuclei. To gain experience with this, a beam test of a stack of three Si(Li) detectors will take place at NSCL by 2021.

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