Mass Resolution of the Scintillating Optical Fiber Isotope Experiment (SOFIE)

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ABSTRACT

In December, 1990, we exposed the Scintillating Optical Fiber Isotope Experiment (SOFIE) to beams of silicon and iron nuclei at the LBL Bevalac accelerator. SOFIE is a Cerenkov–dE/dx–range balloon experiment designed to study the isotopic composition of heavy galactic cosmic rays. Newly developed detectors using scintillating optical fiber technology provide high–resolution trajectory and range measurements in a large–area detector. An Analysis of the Bevalac data is presented, including performance of the trajectory, Cerenkov and range detectors, and mass resolution at silicon and iron. We find the mass resolution to be ~ 0.26 amu at silicon and ~ 0.4 amu at iron, consistent with predictions based on the expected sources of error in the Cerenkov and range detectors.

1 INTRODUCTION

The SOFIE instrument (Hink 1992, Davis 1993) uses the Cerenkov–range technique to measure the isotopic composition of galactic cosmic rays from silicon to iron. The detector stack includes two plastic scintillator dE/dx detectors and a fused silica Cerenkov counter, each in a light–diffusion box viewed by photomultiplier tubes (PMTs). The dE/dx and Cerenkov signals are used to measure the charge of a particle, and charge–changing interactions can be rejected by requiring agreement between the upper and lower scintillators. Pathlength and detector non–uniformity corrections are made using data from the Scintillating Optical Fiber Trajectory (SOFT) Detector, which measures the position of each particle at three points along its path through the instrument. With the charge and trajectory determined, if the particle stops in the range detector, the Cerenkov and range measurements yield the mass of the particle. A third plastic scintillator below the range detector is used to reject penetrating particles and to

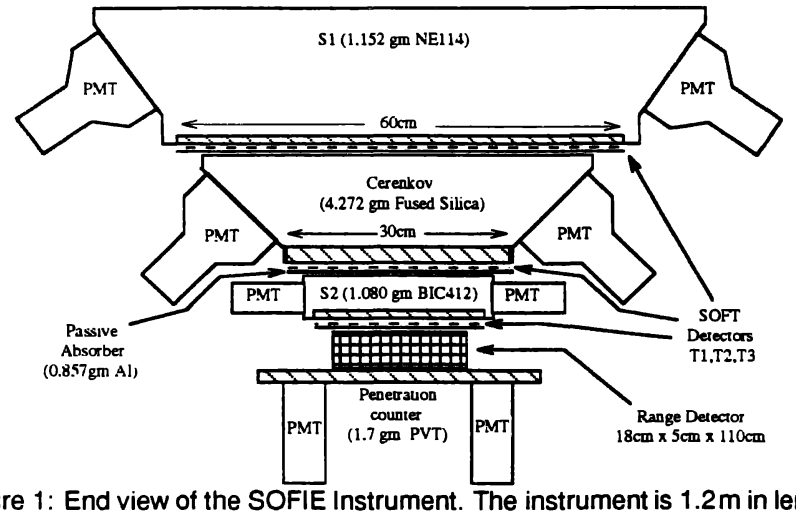

Figure 1: End view of the SOFIE Instrument. The instrument is 1.2 m in length, with a geometry factor of $\sim 0.40\,m^2sr$.

detect fragments from charge–changing interactions. The energy interval analysed is 360–700 MeV/n for iron at the top of the Cerenkov radiator. Data analysis is in progress from a 22–hour balloon flight of SOFIE in August 1991, from Lynn Lake, Manitoba.

2 DETECTOR DESCRIPTIONS

The SOFIE range detector is a coherent stack of 200 μm square scintillating optical fibers. The stack is 110 cm long, 18 cm wide, 5 cm deep, and contains 225,000 fibers. The fibers are manufactured at Washington University, and have a polystyrene core doped with scintillating dyes and an acrylic cladding with a lower index of refraction than the core (see Davis *et al.*, 1989 and Hink, 1992). The deposition of energy by a charged particle as it passes through the range detector causes scintillation light to be generated in the fibers in its path. A portion of this light is piped down the fibers to the end of the range detector, where the track of the particle is recorded by Image–Intensified CCD (II–CCD) cameras. Figure 2 shows a typical stopping iron track recorded in the range detector.

Figure 2: Typical track of an iron nucleus stopping in the range detector.

The SOFT detector also uses 200 μm scintillating fibers. The detector has three planes, each of which consists of two fiber ribbons, where the fibers in the two ribbons are perpendicular. The fibers are supported by 25 μm Kapton[1] film stretched on aluminum frames, the largest of which is 1.2 m x 0.65 m. They are formatted for coupling to II–CCD cameras as shown in Figure 3. Fibers lit up by an incoming particle are

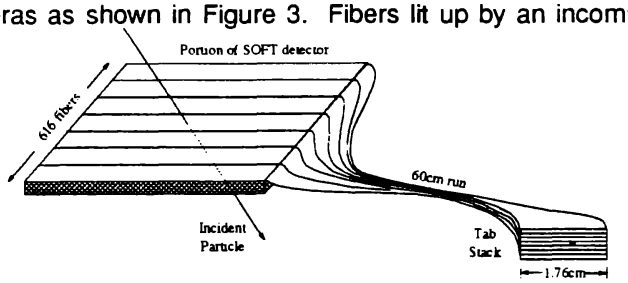

Figure 3: Formatting of fiber ribbons for coupling to an II–CCD camera. The black square in the tab stack indicates a fiber lit up by an incident particle.

recorded as small bright spots in the video data and the particle trajectory is reconstructed from the centroids of these spots. Six cameras are required to read out the SOFT detector.

The SOFIE Cerenkov detector is a light–diffusion box in which a 1.94 cm thick fused silica radiator is viewed by 16 Hamamatsu R877 PMTs. The threshold energy for Cerenkov output is $\sim$340 MeV/n. For the 1990 Bevalac calibration, PMP wave–shifter dye was applied to the PMT faces to increase light yield, resulting in $\sim$95 photoelectrons for $Z = 1$, $\beta = 1$ particles in lab tests.

3 BEVALAC CALIBRATION RESULTS

The primary goals of the calibration were: 1) to measure the efficiency and resolution of the new SOFT detector; 2) to measure the Cerenkov, range and mass resolution and compare with predictions based on computer models; and 3) to verify the functionality of the instrument in preparation for the 1991 balloon flight. To this end, the SOFIE instrument was exposed to beams of ^{56}Fe and ^{28}Si at various incident angles and energies.

Table 1 shows the tracking efficiency (the efficiency with which we can reconstruct particle trajectories) of the SOFT detector for three different cases: 1) no data from

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redundant cameras are used; 2) redundant camera data are used; and 3) redundant data are used, and we require only five out of six fiber ribbons to contribute to the track reconstruction. The data imply an efficiency of 99.4% for a single fiber ribbon at iron, and 92.6% at silicon. The decreased tracking efficiency at silicon is due to the S/N ratio of the low–cost II–CCD cameras used on the instrument. Multiple scattering in the

TABLE 1: SOFT Detector Tracking Efficiency

Beam	Energy* (MeV/n)	Angle (Degrees)	Tracking Efficiency (%)		
			Case 1	Case 2	Case 3
^{56}Fe	549	27.6	96.5	98.2	99.4
^{28}Si	413	40.8	63.0	78.0	91.3

*Energy at top of Cerenkov radiator

materials between the planes of the SOFT detector dominates the trajectory resolution, resulting in an apparent position resolution in each plane of $\sim 350\,\mu$m at iron. This does not significantly degrade the mass resolution.

Figure 4 shows Cerenkov vs. range data for silicon and iron beams at various energies, after charge selection cuts made using the scintillator detectors. The data have also been corrected for detector areal non–uniformities and variations in incident angle, using trajectory data from the SOFT detector. Also shown are mass lines from a

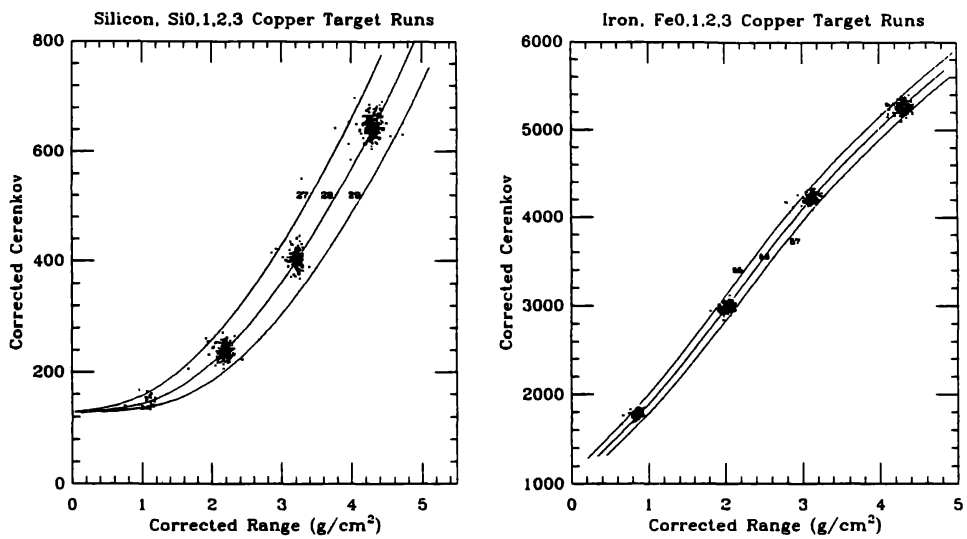

Figure 4: Cerenkov and range data for silicon at 40.8° incident angle, and iron at 27.6°, at various energies. Mass lines from the Cerenkov–range response model are superimposed.

Cerenkov–range response model developed for the SOFIE experiment, the parameters of which were derived from a simultaneous fit to the iron and silicon calibration data. The model includes the effects on the Cerenkov response of residual scintillation, knock–on electrons, optical properties of the detector materials, and slowing down of the primary particle in the radiator. Energy losses are calculated using code based on that of Benton and Henke (1969). This model is evidently in good agreement with the calibration data, and is used to determine the mass scale.

Figures 5 and 6 show the Cerenkov, range and mass resolution, for the same data as shown in Figure 4. Superimposed are resolution predictions based on the known sources of error. For the Cerenkov, the important sources of error are photoelectron statistics, fluctuations in the number and energy of knock–on electrons (Grove and Mewaldt, 1993), and detector response mapping residuals. For the range, they are detector thickness variations, multiple scattering, range straggling, and track measurement uncertainties. For silicon, we find good agreement between predicted and achieved Cerenkov, range and mass resolution, achieving ~ 0.26amu mass resolution at 390MeV/n. For iron, we also find good agreement between predicted and achieved

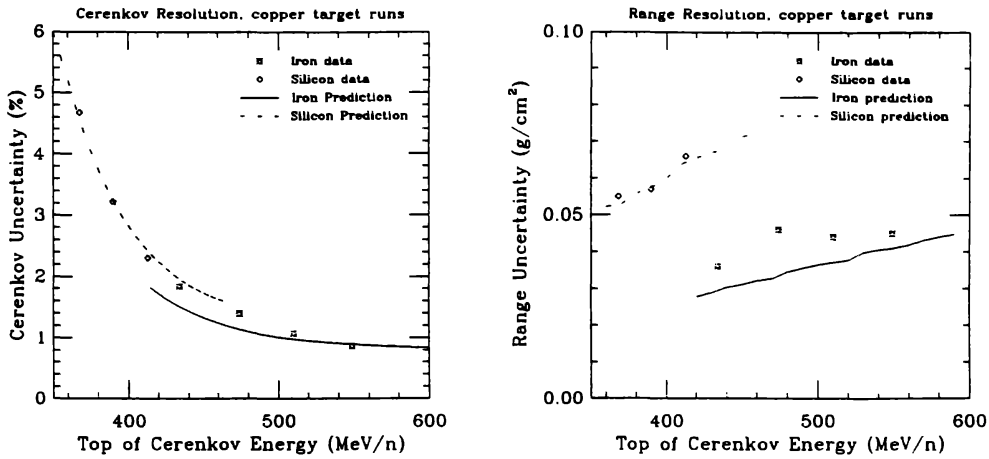

Figure 5: Comparison of predicted and achieved Cerenkov and range resolution, at silicon and iron. Same data as in Figure 4.

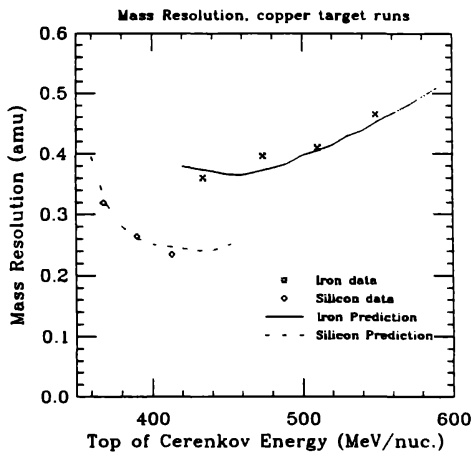

Figure 6: Comparison of predicted and achieved mass resolution, at silicon and iron.

mass resolution, achieving ~ 0.40 amu at 475 MeV/n. The Cerenkov and range resolution at iron is not as good as predicted, but we believe this is due to broadening of the beam energy in copper targets used to modulate the energy upstream of the experiment.

4 CONCLUSIONS

The mass resolution of the SOFIE instrument is as good as, or slightly better than the best cosmic ray iron isotope experiments yet flown. Our Cerenkov–range response model is in good agreement with the calibration data and we understand the resolution limitations of the detectors. Data analysis of the 1991 balloon flight from Lynn Lake, Manitoba, is in progress.

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