1987ICRC....2..382C

1987-16

HIGH RESOLUTION CERENKOV DETECTORS FOR USE IN A COSMIC RAY ISOTOPE SPECTROMETER

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Abstract

We describe the development of new high-resolution Cerenkov detectors for use in an instrument designed to measure the isotopic composition of cosmic ray nuclei from Be to Ni ($Z = 4$ to 28). The latest version of this balloon-borne instrument contains two new large-area (~0.5 m^2) Cerenkov detectors, one composed of Teflon and a second of Pilot-425. Through the use of improved light-collection techniques, and a novel radiator design, the photoelectron yield of these counters has been upgraded significantly over that of earlier counters. In particular, the greatly improved Cerenkov light yield achieved with Teflon makes it an attractive alternative to available liquid counters of similar index of refraction. Laboratory tests of these and other Cerenkov radiators are described, along with estimates of the mass resolution that can be achieved.

1. Introduction. Over the past several years we have been developing an instrument designed to make high-resolution measurements of cosmic ray isotopes. The High-Energy Isotope Spectrometer Telescope (HEIST) consists of a stack of 12 NaI(Tl) scintillators (L1 to L12) totaling 88 g/cm^2, two Cerenkov counters (C1 and C2), and two plastic scintillators (S1 and S2), as illustrated in Figure 1. Each of the 2-cm thick NaI disks is viewed by six 1.5-inch photomultipliers (PMTs) whose combined outputs measure the energy deposition in that layer. In addition, the six outputs from each disk are compared to determine the position at which incident nuclei traverse each layer to an accuracy of ~2mm. The Cerenkov radiators are each enclosed in light integration boxes and viewed by sixteen 5-inch PMTs (RCA "teacup"). This experiment is a collaborative effort of Caltech, UNH, and the Danish Space Research Institute.

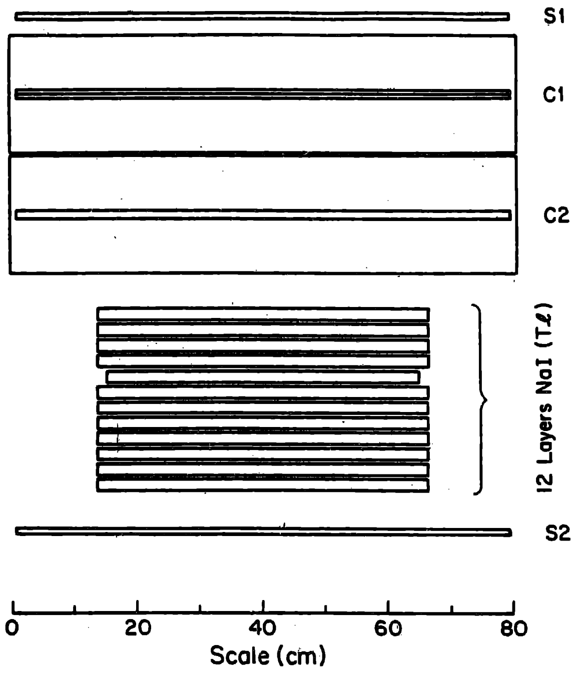

Figure 1. Schematic of the HEIST-2 instrument

HEIST determines the mass of individual nuclei by measuring both the change in the Lorentz factor ($\Delta\gamma$) that results from slowing down and stopping in the NaI stack, and the energy loss (ΔE) in the stack. Since the total energy of an isotope is given by $E = \gamma M$, the mass M can be determined by $M = \Delta E/\Delta\gamma$. HEIST is designed to achieve a typical mass resolution of 0.25 amu.

The energy range covered by HEIST can be "tuned" by choice of the index of refraction (n) of the two Cerenkov counters. An earlier version of the instrument (HEIST-1; see [1] and references therein) was "tuned" for energies from ~1.5 to 2 GeV/nuc, and was flown in 1984. In its present configuration

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(HEIST-2, see Figure 1) C1 is composed of Teflon (n=1.33), C2 is Pilot-425 (n=1.50), and the instrument is capable of resolving isotopes over the energy range from ~0.4 to ~1.1 GeV/nuc. In HEIST-2 the Cerenkov counters provide two independent measurements of the mass of nuclei which stop in the NaI stack, giving improved mass resolution over the initial version of the instrument. In addition, the expected yield of isotope events is greatly increased, and isotope resolution is extended to lighter elements.

In this paper we describe the various techniques employed to optimize the performance of the HEIST-2 Cerenkov counters. In addition, we present the results of an analysis of the various contributions to the mass resolution that result from the velocity measurement provided by the Teflon counter.

2. Cerenkov Counter Developments. The velocity resolution of a Cerenkov counter is often limited by statistical fluctuations in the number of photoelectrons produced in the PMTs viewing the radiator. In order to maximize the yield of photoelectrons (PEs), we have made improvements in the following areas.

Wavelength Shifters: The PE yield increases significantly with the fraction of UV Cerenkov light that can be "waveshifted" to longer wavelengths where the quantum efficiency of the PMTs is greater, and where absorption in the Cerenkov radiator, the $BaSO_4$ paint, and the PMT glass windows is reduced. Using a variation of the P-terphenyl (PTE) wave-shifter employed by the New Hampshire group [2], we have succeeded in doubling the photoelectron yield from both fused silica and Teflon radiators by applying waveshifter to the radiator surfaces. For large area counters of the type described here, we have developed a spray technique in order to ensure uniformity of application.

Teflon Radiators: Teflon is a useful Cerenkov radiator because of its low index of refraction. Although water has the same index and various flourochemical compounds have similar indices, they suffer from the difficulty of working with a liquid. Of the wide varieties of Teflon available, we tested several expected to have excellent optical characteristics and found definite differences in their Cerenkov light output. These differences were considerably magnified when wave-shifter was applied, presumably because of differences in UV transmission. Even the best type of Teflon (pure TFE) shows variations of ~20% from sample to sample. As a result of these improvements, and also the sandwich technique described below, we now collect as large a fraction of the theoretical Cerenkov yield from Teflon as we do from Pilot 425 and fused silica.

Cerenkov Sandwiches: We have also developed a new technique that further improves the light output of Teflon, and which may have application to other radiators such as aerogel. We found that a sandwich of two pieces of Teflon, each wave-shifted, produces ~13% more PEs than a single piece of equivalent total thickness, presumably because the internal layer of waveshifter permits additional UV light to be shifted before it suffers attenuation. The light yield is further increased in going to additional layers, but soon reaches a point of diminishing return.

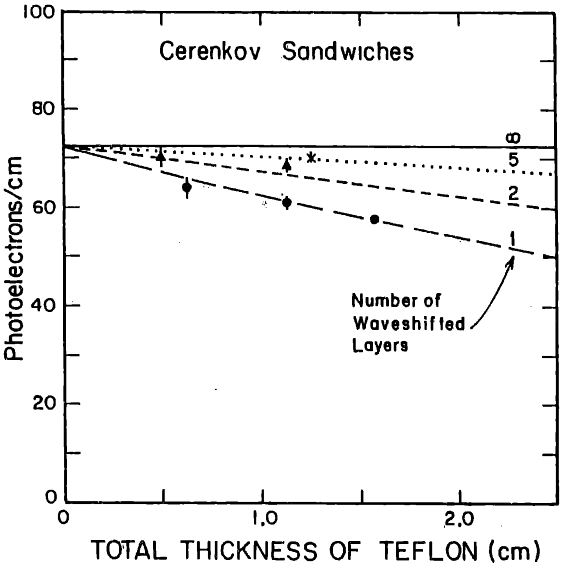

Figure 2. Photoelectron yield vs. total Teflon thickness for various layers of waveshifted Teflon. Experimental values for 1 layer (solid circle); 2 layers (triangles); and 5 layers (crosses) are compared to a simple attenuation model with one free parameter

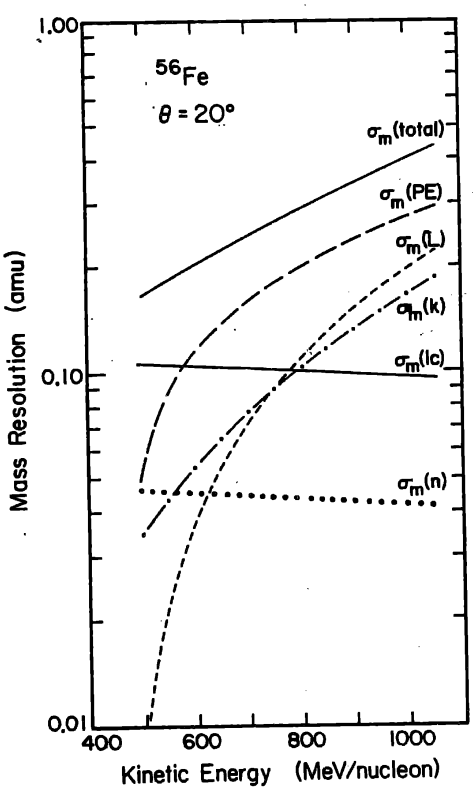

Figure 3. Contributions to mass resolution for ^{56}Fe at $\theta = 20°$ from the Teflon counter, including PE statistical fluctuations σ_m(PE), Landau fluctutions σ_m(L), fluctuations in the secondary Cerenkov light from knock-on electrons σ_m(k), and stochastic variations in light-collection efficiency σ_m(lc) and index of refraction σ_m(n). Not shown but included in the total mass resolution σ_m(total) for the instrument is a 0.1 amu contribution from the NaI stack. Note that mass resolution improves for lower Z nuclei

Figure 2 summarizes several of these tests along with a fit to the data based on a simple model with one free parameter for the average attenuation length of unshifted Cerenkov light in Teflon. We plan to try this technique with other radiators, including aerogel.

High-Reflectance Paints: To improve the light-collection efficiency of our integration boxes, we have tested a variety of high-reflectance barium sulfate paint mixtures and other materials, including millipore and Teflon sheeting, by substituting test plates for two of the six walls of a small test chamber. The best results were obtained with $BaSO_4$, although significant differences were noted depending on the purity and proportion of $BaSO_4$ used. By increasing this proportion we developed a paint that tested 2% better (presumably 6% better when the whole box is covered) than the standard GSFC mixture in widespread use for the last decade or so [3].

As a result of these developments, we have achieved a light yield of ~75 photoelectrons per β=1, Z=1 particle in the 1.6 cm Teflon radiator of HEIST-2. This yield (per cm) is ~3 times that achieved in a Teflon counter of similar area flown on HEAO-3 [4], and as noted above, the light-collection efficiency that we achieve for Teflon is comparable to that of any radiators tested in similar area counters. For the Pilot-425 counter we have achieved ~115 photoelectrons from a 2.2 cm thick radiator, to our knowledge the best so far achieved (per cm) in a counter of this area. Although many of the improvements that we have achieved are small individually, when added together they result in substantially better performance—a key to achieving excellent mass resolution over a broad energy range.

3. Contributions to Mass Resolution. In a Cerenkov-total energy spectrometer the mass resolution is typically dominated by the uncertainty in the velocity measurement. We have modeled the various contributions to the mass resolution of HEIST-2 from the Teflon counter, with the results for ^{56}Fe at zenith angle $\theta = 20°$ shown in Figure 3.

For large-angle particles, uncertainty in the trajectory can produce an unacceptably large mass uncertainty. We can alleviate this problem by determining velocity, not from the pathlength-corrected Cerenkov signal, but from the ratio R of the Cerenkov signal to the dE/dx signal from the nearest NaI stack layer ($R \equiv C/S$). Pathlength effects are therefore removed automatically, with the only source of error the small effect of multiple Coulomb scattering in the few grams of radiator and NaI. However, dividing by S introduces Landau fluctuations in the energy loss in the stack layer into the velocity measurement. We have, therefore, traded a contribution from trajectory uncertainty for a contribution from Landau, but the latter is smaller for typical angles and reasonable angular resolution (~1°).

Of the remaining contributions to mass uncertainty, photoelectron statistical fluctuations dominate, with the PE contribution typically about twice the Landau contribution (see Figure 3). Both are proportional to the mass to charge ratio A/Z. There is another benefit to using R. One can show that the mass uncertainty due to PE fluctuations $\sigma_m(\mathrm{PE}) \propto [\ \partial R/\partial\gamma\ ]^{-1}$. Since the Cerenkov signal is an increasing function of γ, and the dE/dx signal a decreasing function, determining velocity from the C/S ratio further improves mass resolution by increasing the variation of the signal with respect to the particle velocity. For example, at 750 MeV/nuc the PE contribution to the mass resolution determined from R is approximately 80% of that determined directly from the Cerenkov response. Also at 750 MeV/nuc and $\theta = 20°$, the sum in quadrature of the PE and Landau contributions determined from R is approximately 60% of the sum of PE and trajectory contributions, assuming a 1° angular resolution, determined from C alone.

Fluctuations in the number and, more importantly, the energies of knock-on electrons produced above and within the radiator also contribute to the mass error. We have calculated the knock-on Cerenkov light and its rms variation by numerical techniques, using a procedure similar to that of Lezniak [5]. We find, again for example for ^{56}Fe at 750 MeV/nuc, that the knock-ons generate about 5.5% (with an rms variation of 0.3%) of the primary Cerenkov light at that energy. We see in Figure 3 that the knock-on contribution is non-negligible and approximately equal to the Landau contribution. Note that the knock-on contribution $\sigma_m(k) \propto A/Z$.

There are other potential contributions to mass resolution which, while not of a fundamental nature, must be carefully controlled. Variations in light-collection efficiency can be mapped either at an accelerator or in flight, but residual small-scale variations which are not removed by the maps will lead to an uncertainty in mass. In addition, while gross variations in index of refraction will masquerade as light-collection non-uniformities and be included in the maps, small-scale index variations may also lead to mass uncertainty. Figure 3 shows that a residual rms variation in light collection uniformity of $\sigma_{lc} \approx 3\times10^{-3}$, where the uniformity is nominally 1, is necessary to reduce this contribution to 0.1 amu for ^{56}Fe. Although to date we have no measurement of the index variation for Teflon, we have assumed here a residual rms variation of $\sigma_n \approx 3\times10^{-4}$, the value we determined for an aerogel radiator of index n = 1.1. Because of differences in the methods of manufacture of aerogels vs. Teflon, we expect that σ_n will be smaller in Teflon. Both of these contributions are proportional to A but independent of Z, and therefore tend to be insignificant for lighter nuclei.

Similar velocity resolution is obtained from the Pilot-425 counter and, in the region where the useful energies of the two Cerenkov counters overlap, the final mass resolution is correspondingly improved. As a result of the Cerenkov counter developments described here, HEIST-2 should be capable of resolving a wide range of cosmic ray isotopes from Be to Ni over the energy range from ~0.4 to ~1.1 GeV/nuc. We expect to fly the instrument from northern Canada during the summer of 1987.

4. Acknowledgements. We are grateful to E. C. Stone for important contributions to this work. We also thank N. Vogt for help in the Çerenkov counter fabrication and testing. Supported in part by NASA under grants NGR 05-002-160 at Caltech and NGR 30-002-052 at UNH.

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