A CERENKOV - ΔE/ΔX EXPERIMENT FOR MEASURING COSMIC-RAY ISOTOPES FROM NEON THROUGH IRON

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ABSTRACT

A balloon-borne cosmic-ray experiment has been constructed to measure cosmic-ray isotope masses. It employs a pair of Cerenkov counters and a NaI scintillator stack to determine changes ΔE in energy and $\Delta\gamma$ in Lorentz factor for a traversing or stopping particle. Mass $M = \Delta E/\Delta\gamma$. Mass resolution better than 0.3 a.m.u. is expected for incident elements from neon through iron, with incident Lorentz gammas ranging from 2.4 to 3.1, depending on the element. Using data obtained at the Berkeley Bevalac, the mass resolution $\delta M \approx 0.2$ a.m.u., measured for ^{55}Mn ions with incident $\gamma = 2.75$.

1. INTRODUCTION

The availability of silica aerogels as solid Cerenkov radiators with low indices of refraction has the prospect of good isotope mass resolution up to several GeV/nucleon (Cantin et al. 1975). Meyer and Gaulier (1975) describe a method of isotopic analysis for cosmic rays using two Cerenkov counters and an absorber. Additional detectors provide trajectory information, required for correcting nonuniform spatial response of the counters, and for deducing the expected energy deposition ΔE in the absorber and the path length in the Cerenkov counters. The method can be applied only if the particle penetrates the absorber and is "onscale" in both of the Cerenkov counters.

The apparatus described here is an improved version of the Meyer and Gaulier method. It provides better rejection against fragmenting events and does not require separate trajectory measurements. Particles need not penetrate the apparatus for a mass determination. For stopping particles, the method resembles the Cerenkov-range technique of Fisher et al. (1976), or the Cerenkov-E technique of Webber et al. (1973). Figure 1 is a schematic diagram. A stack of twelve NaI(Tl) discs 52 cm in diameter and a total of 87.2 gm/cm^2 in thickness directly measures ΔE. Each stack layer is viewed by six individually digitized photomultipliers. This arrangement measures not only the energy deposition, but also the trajectory location in the layer (Buffington, Lau and Schindler 1981). A direct measurement of ΔE reduces the dependence of the experiment upon accurate trajectory measurements, and independent determinations of response in many stack layers provide a means of removing the numerous events fragmenting within the stack. Plastic scintillators above and below the apparatus provide further rejection against events fragmenting in the Cerenkov counters. Typically 15% of the incident particles escape fragmentation reactions, and thus can be successfully analyzed. The refractive indices of the two Cerenkov counters, $n = 1.1$ (aerogel) above and a combination of $n = 1.34$ (teflon) and $n = 1.49$ (Pilot 425) below, fix the range of incident charge Z and velocity γ covered by the experiment.

2. BASIC FORMULAE

The Cerenkov counters measure the incident and outgoing Lorentz gamma factors γ and γ' for particles passing through the NaI stack. Of course, if the particle stops within the stack, $\gamma' = 1.0$. Taking $\Delta\gamma \equiv \gamma - \gamma'$, mass M is given by

$$M = \Delta E / \Delta\gamma \qquad (1)$$

For uncertainties $\delta\Delta E$ and $\delta\Delta\gamma$ in ΔE and $\Delta\gamma$ respectively, mass error δM is given by

$$\delta M = M \left((\delta\Delta E/\Delta E)^2 + (\delta\Delta\gamma/\Delta\gamma)^2 \right)^{1/2} \qquad (2)$$

Figure 2 shows the fraction f of relativistic Cerenkov light as a function of γ for the various indices of refraction. The slope $df/d\gamma$ of the appropriate curve relates δf, the uncertainty from a given Cerenkov counter, to $\delta\Delta\gamma$. Photoelectron statistical fluctuations in the Cerenkov counters provide a fundamental limit to the accuracy with which $\Delta\gamma$ can be determined. For N photoelectrons to be observed in a Cerenkov counter, $N = Z^2 f N_{rel} \sec\theta$, where f is obtained from the particle's γ and figure 2, N_{rel} is the photoelectrons detected for a high energy $Z = 1$ particle, and θ is the incident angle. The resulting mass error for one Cerenkov counter is then

$$\delta M_{pe} = \frac{M \, d\gamma/df \, (f/N_{rel} \sec\theta)^{1/2}}{Z \, \Delta\gamma} \qquad (3)$$

This equation can also be expressed without reference to f:

$$\delta M_{pe} = \frac{M \, n^2 \, \gamma^3 \, (1-1/n^2)^{1/2} \, (1-1/\gamma^2-1/n^2)^{1/2} \, (1-1/\gamma^2)^{3/2}}{2 \, Z \, \Delta\gamma \, (N_{rel} \sec\theta)^{1/2}} \qquad (4)$$

Since in first order the responses of both a Cerenkov counter and a nearby scintillator layer are proportional to $Z^2 \sec\theta$, the dependence of the experiment upon pathlength can be significantly reduced if γ and γ' are calculated from the ratios of these responses. However, this method of analysis allows Landau fluctuations in the scintillators to contribute to $\delta\Delta\gamma$. For a 2 centimeter thick NaI scintillator,

$$\delta M_{landau} = \alpha \frac{M \, \gamma^3 \, \beta^2 \, (1-1/\gamma^2-1/n^2)}{2 \, Z \, \Delta\gamma} \qquad (5)$$

where $\beta^2 = 1-1/\gamma^2$, with α varying between 0.08 and 0.14 depending on the Cerenkov counter and the velocity.

The experiment is designed so iron events near Cerenkov threshold incident at about 45° penetrate at least five NaI layers, and so most iron events stop within the stack. Lower charges penetrate more and thus, if they escape the stack, require analysis of the lower Cerenkov counter and plastic scintillator responses to determine the mass. The full geometry factor of the apparatus is about 0.25 m^2ster. The range in γ for good mass resolution is set by the Cerenkov threshold on the low end, and by the γ^3 factor on the high end. The range of good mass resolution diminishes slowly with increasing Z, tracking the slow increase of M/Z. The cutoff below about $Z = 10$ is set by the stack thickness and the regime of good performance ($f \leqslant 0.5$) for the lower Cerenkov counter.

In two other papers presented at this conference (Schindler et al. 1983; Rasmussen et al. 1983), we describe preliminary analysis of Bevalac calibrations for the NaI stack and the aerogel Cerenkov counter. The calibration with ^{55}Mn at $\gamma = 2.75$ shows $\delta\Delta E/\Delta E \leqslant 0.0025$, thus yielding a 0.14 a.m.u. upper limit to the mass error contribution. Contributions at other values of Z and γ are expected to be comparable. Mass error contributions for the Cerenkov counters are dominated by the two mechanisms discussed above. The expected Cerenkov contribution to mass error is presented in figure 3, with results of the recent calibration. The position resolution achieved in the calibration (± 1.7 mm) is adequate for correcting spatial response variation in the detectors.

3. BALLOON FLIGHT SYSTEM

A number of distinctive features of the instrument are worth describing. All 108 photomultipliers viewing the various detectors are individually digitized. This information is transferred to a Texas Instruments TMS 9995 microprocessor which combines them with time and housekeeping information, and places the resulting event information into a buffer memory storing 200 events. The data are then formatted and transferred to each of two onboard commercial video recorders, which record two sequential copies of each event, with 16 bits per horizontal line. Between the event blocks, the recorders are held in the "pause" mode, significantly reducing tape consumption. The video recorders, operated in parallel for redundancy, each have a storage capacity of about 4×10^5 events, corresponding to five days of data with the expected event rates for a flight from Palestine, Texas. Detectors and photomultipliers are kept at a constant 25°C in the presence of a heat input of about 300 watts from the electronics, and the day-night variable heat input from outside of the gondola shell, by a passive insulation barrier coupled with an on-board evaporative cooler. This cooler holds about 30 liters of water and is vented to the outside. A servo system regulates the cooler power, which instantaneously is about -600 watts with the water at 10°C. Telemetry and ground command allows adjustment of trigger thresholds in the top plastic scintillator and the fifth stack layer with the nominal threshold near high energy carbon response. The payload weighs about 1000 kg and is expected to be ready for balloon flight later this year. This work is supported in part by Grant NGR 05-002-160 of the National Space and Aeronautics Administration.

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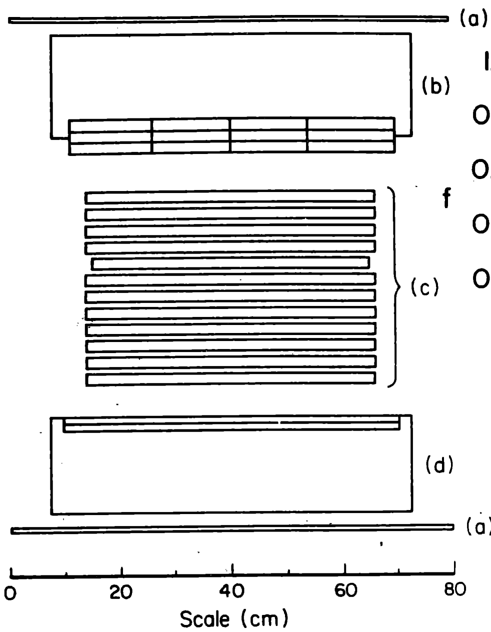

Fig. 1. Schematic diagram of the experimental apparatus. (a) plastic scintillators; (b) aerogel Cerenkov counter; (c) NaI scintillator stack; (d) bottom Cerenkov counter with Pilot 425 and teflon. Large rectangles show Cerenkov light collection boxes.

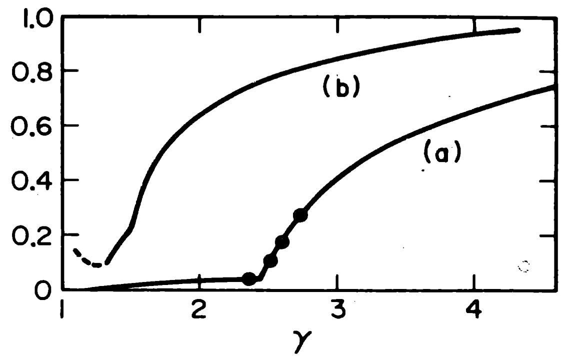

Fig. 2. Calculated fraction of relativistic Cerenkov light made by particles of energy γ = E/M incident on the radiators for this apparatus. (a) aerogel. (b) Pilot 425 and teflon combination, equal light contribution from both for relativistic particles. The calculation includes Cerenkov light from δ-rays and the light integration box paint, as well as a 3% scintillation contribution for the Pilot 425. The four data points on the aerogel curve are from the ^{55}Mn Bevalac data.

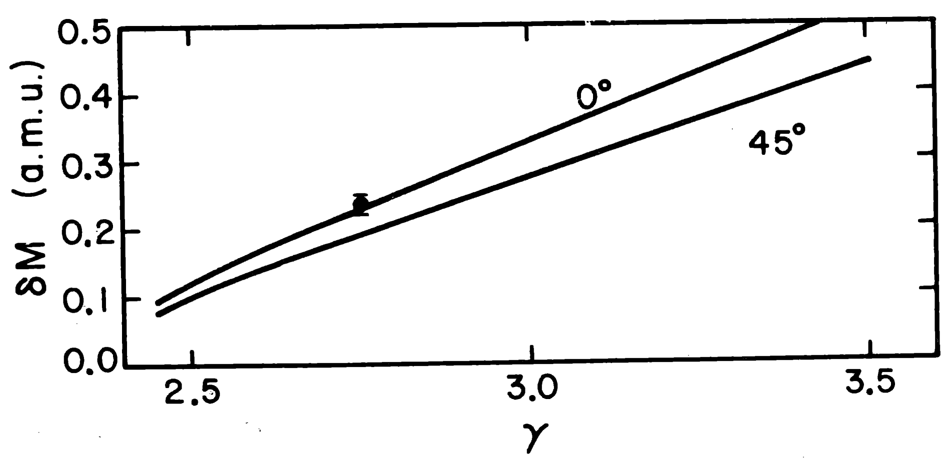

Fig. 3. Calculated mass error δM for stopping events as a function of incident γ, from the Cerenkov counter. Results are presented for two incident angles. The curves assume 23 photoelectrons for relativistic charge one, and a contribution from δ-ray fluctuations of 1.4 Z photoelectrons. The data point is from the Bevalac calibration.