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CALIBRATION OF A STACK OF NaI SCINTILLATORS AT THE BERKELEY BEVALAC

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ABSTRACT

A stack of twelve NaI(Tl) discs, 2 cm thick each, has been exposed to sea level muons, and to beams of relativistic carbon, neon, argon, and manganese at the Berkeley Bevalac. For ^{55}Mn with $\gamma = 2.75$, the position-measuring accuracy of individual discs is better than ±2 mm, individual layer responses are close to the Landau distribution, and residual error for measuring total kinetic energy of the stopping ions is less than 0.25%.

1. INTRODUCTION

In another paper of this conference (Buffington et al. 1983), we describe a Cerenkov-ΔE experiment for measuring cosmic-ray isotope masses from neon through iron. A major component of this experiment is a stack of 12 NaI(Tl) discs, typically 52 cm in diameter and 7.3 gm/cm^2 thick, which measures both position and ΔE. NaI(Tl) is suitable for this purpose because it is a hard, homogeneous material capable of being ground and polished to an optical finish; and because for a given stopping power it causes fewer fragmentation reactions than does plastic. In addition, NaI(Tl) is efficient at converting dE/dx energy losses into visible light, and this efficiency remains more constant with the large dE/dx values for heavy ions than it does for plastic scintillator (Salamon and Ahlen 1981, 1982). The discs were prepared in a similar fashion to that previously described (Buffington, Lau and Schindler 1981), except here they are each viewed by six photomultipliers rather than four, and the photomultipliers are mounted within the hermetic can. The 72 photomultipliers are individually digitized, thus permitting measurement of the particle's transverse (x,y) coordinates and energy deposition in each layer. A muon passing through the stack near the axis yields typically 10^2 photoelectrons in each photomultiplier. The individual-layer energy deposition measurements are constrained in the data analysis to fit a proper Bragg energy deposition curve for the isotope, and the resulting fit is effective in removing most types of fragmenting-particle events. The position information can be used to correct (x,y)-dependences in the responses of the individual NaI stack layers, and also provides the trajectory information for similar corrections in the Cerenkov counters and plastic scintillators above and below the stack. In this paper we describe a calibration of the NaI stack with beams of heavy ions from the Berkeley Bevalac.

2. BEVALAC EXPOSURE

The stack was exposed to Bevalac carbon, argon, and neon beams in June 1981, and to a manganese beam in November 1982. This latter provided the data for the principal calibration of the instrument. For the ^{55}Mn exposure, the Bevalac was operated with the ions in the +24 charge state, yielding upstream particles with 1.75 GeV/nucleon. When the beam reached the front (top) plastic scintillator, material traversed, mostly air, had reduced the energy to 1.71 GeV/nucleon. The particle position was recorded by wire chambers in front of the apparatus. In the absence of fragmentation reactions, the ^{55}Mn stops in layer 12. The energy deposition in this layer agrees with that expected from dE/dx calculations; the overall energy deposition in the stack agrees with that expected within about 1%. Data were acquired at a variety of apparatus positions, to provide an adequate response map for the NaI stack scintillators and front Cerenkov counter. Additional data were acquired near the stack axis with varying amounts of upstream material, and with the apparatus turned at 30° and 180°.

3. NaI RESPONSE

The photomultiplier gains were balanced using on-axis events from the front and rear entry beam exposures. Layer-to-layer gain adjustment was performed by fitting to the expected Bragg curve through the apparatus. There is good agreement for this adjustment comparing middle layers for the front and rear entry data. Values of light output/energy deposition, dL/dE, are then obtained for the final four layers before the ^{55}Mn stopped. Figure 1 shows the result, together with data from Salamon and Ahlen (1981), and our layer 1 value for Mn normalized to agree with an extrapolation of their data. Values of dL/dE at smaller values of dE/dx are also obtained from the Bevalac data having 5 cm of polyethylene placed in the beam upstream. This material caused substantial fragmentation of the Mn in the beam, and individual charges down to magnesium can be discerned. The observed layer 1 NaI responses are plotted in figure 1 versus the calculated values of dE/dx. There appears to be good agreement with the findings of Salamon and Ahlen (1981), and for these charges and values of dE/dx, the saturation in dL/dE depends mainly on dE/dx and very little on charge Z. A similar comparison of response in the NE-110 plastic front scintillator agrees well with an extrapolation of the data, for this material, of Salamon and Ahlen (1982).

4. POSITION RESOLUTION

The position resolution of the stack layers is determined by comparing the wire chamber coordinates to those inferred from the ratios of opposite photomultiplier response. A preliminary analysis has been performed only near the stack axis, where contours of equal response ratio are reasonably straight. Figure 2 shows the difference between the observed wire chamber coordinates and the prediction from the logarithm of the ratio of two opposite photomultipliers, suitably scaled, for ^{55}Mn ions in layer 4. The distribution is Gaussian, with $\sigma = 1.7$ mm. This value can be understood as the quadrature of photoelectron fluctuations, wire chamber uncertainty, and multiple Coulomb scattering spreading the beam angle. As the particles pass deeper into the stack, additional multiple Coulomb scattering gradually spreads the beam, until $\sigma = 2.6$ mm in the rear layer where the ^{55}Mn stops. The intrinsic spatial resolution for ^{55}Mn ions, when these contributions are unfolded, is about 1.3 mm. Figure 3 presents this result, together with muon, carbon, and neon data, displayed versus the square root of the response. At least near the axis, the stack position resolution is close to the fundamental limit set by photoelectron statistical fluctuations. A residual systematic error of about 1 mm appears to be present in the Mn point, but the data with lower response follow the expected scaling law.

5. ENERGY DEPOSITION AND STACK RESOLUTION

Each of the stack layers was corrected empirically for response variation, down to about a 0.7% residual error, using linear and quadratic terms in (x,y). Figures 4 and 5 show the resulting responses in layer 1, and with all layers added, for stopping ^{55}Mn; fragmenting events are removed by requiring no penetration beyond the expected stopping point in the stack. The shape of the distribution in figure 4 is close to that expected combining the Landau distribution for that layer with the residual mapping error. Delta ray fluctuations contribute to the distribution width in figure 5, since the delta rays generate light at a value of 0.365 in figure 1 (Salamon and Ahlen 1981), while the penetrating core of the energy deposition profile explores the lower portions of the manganese curve. Additional contributions come from the intrinsic Bevalac beam spread, residual mapping errors, and photoelectron fluctuations in the stack. Each of these mechanisms is estimated to contribute about 0.1% to the residual uncertainty. We regard the observed $\sigma = 0.25\%$ as an upper limit, since we expect to reduce the residual mapping errors, and the Bevalac beam spread is not intrinsic to the apparatus.

6. DISCUSSION

In considering the role of the NaI stack in the isotope mass measurements for the balloon-borne experiment (Buffington et al. 1983), the trajectory- and energy-measuring capabilities appear to be adequate. Analysis of the carbon and argon data has shown that essentially all of the charge-changing fragmentation reactions within the stack can be identified and removed by the imposition of simple criteria relating the observed energy deposition profiles to the expected Bragg curve depositions. These criteria are even capable of identifying approximately one-third of the expected neutron-stripping interactions, which in these cases have anomalous deposition profiles. The contribution to mass error from uncertainty in ΔE has an upper limit of 0.25% for Mn, which produces an associated mass error for the experiment of about 0.14 a.m.u. This uncertainty should change little with changing γ. Residual errors in the mapping produce even smaller mass errors for lighter isotopes, while photoelectron fluctuations and δ-ray effects are roughly the same independent of charge and energy deposition. Further analysis of the calibration data is necessary before we can prove these results hold throughout the NaI stack, particularly in those regions of the NaI layers where one or more of the photomultipliers cannot view the light directly. Partially supported by NASA grant NGR 05-002-160.

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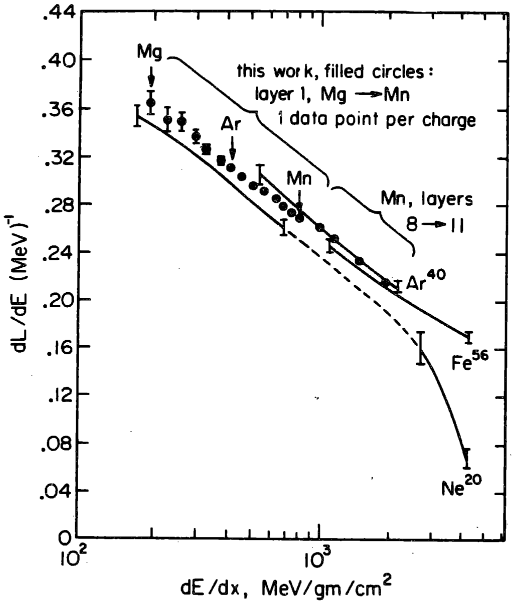

Fig. 1. Saturation of NaI(Tl) response versus dE/dx. Smooth curves from Salamon and Ahlen (1981). Dashed portion couples Salamon and Ahlen's two measurement regimes. Round dots, this work. Overall normalization for this work was provided by placing the layer 1 Mn point on an extrapolation to smaller dE/dx of the iron curve of Salamon and Ahlen.

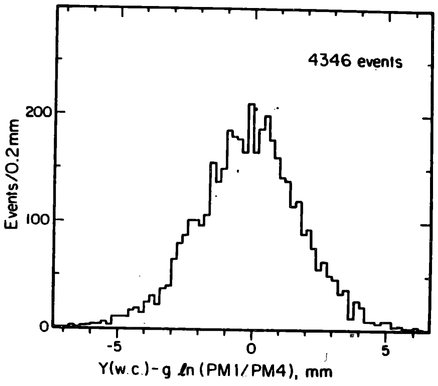

Fig. 2. A plot of the difference distribution between wire chamber coordinates and NaI stack coordinates, ^{55}Mn ions near the axis of layer 4.

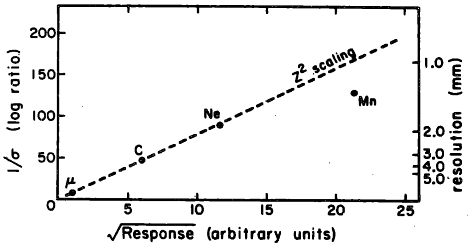

Fig. 3. Inverse NaI spatial resolution versus response. Straight line indicates expected performance if photoelectron statistical fluctuations are the only source of error.

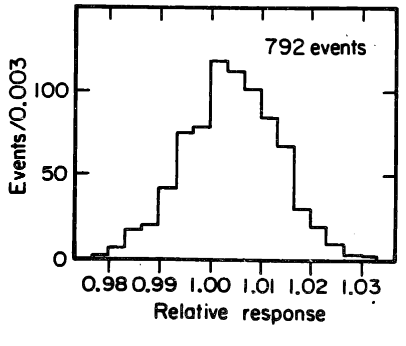

Fig. 4. Distribution of layer 1 response for ^{55}Mn near stack axis.

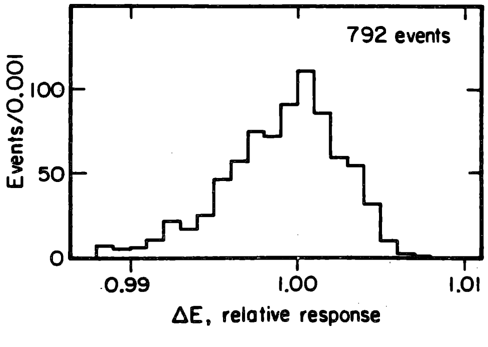

Fig. 5. Distribution of total stack response ΔE for stopping ^{55}Mn.