PREFACE

Appendix G of the Calibration of the High Energy Telescopes for the Voyager and ISEE Cosmic Ray Experiments (CSC/TM-81/6280) has been expanded to include a discussion of the range-energy relation. The attached pages should replace the corresponding pages in the original document. Each revision is marked by a vertical bar in the right margin; the date of the revision is shown in the lower right corner. The original COMDEX number on the document cover and title page should be changed to CSC/TM-81/6280UD1.

TABLES

APPENDIX G

DON REAMES ON TESTA

Programs on the PDP 11/70

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1. Introducton

Programs have been written on the PDP 11/70 that allow generation of response tables ("boxes") for particle telescopes whose complexity does not exceed that of the Voyager-ISEE HET telescopes. Response is based upon an internally generated range/energy relation for silicon that is calibrated to a few percent accuracy for particle species from protons through Fe at energies from below 1 MeV/AMU through ionization minimum (2.4 GeV/AMU) Heavier species and thinner detector elements (<10 microns) may also be used, but with greater uncertainty.

The program TESTA accepts a detector description file as input and produces calculated track files on disk for the detector modes and particle species requested.

The program PLOTPR uses the track file from TESTA to produce any number of printer plots of theoretical response matrices. The desired plots are selected interactively at the CRT terminal.

The program BOXGEN or AUTOBOX uses the track file data from TESTA to generate response tables in a form suitable for input to the FLXPLT program on the IBM 360.

An additional program, PLOTVG, was written to plot response curves on the vector general plotter. However, partly because of VG limitation, the part of the program that would allow measurements to be compared with the curves has not been implemented.

2. Track Calculations-TESTA

Most of the physics of the detector system and its response to particles is determined by the TESTA program; the main task of the other programs is to reformat the output from TESTA.

2.1 Detector Description File:

The input to TESTA is a detector description file such as that shown in Figure 12 b. Records beginning with C in the first column are treated as comments and are not analyzed by the program. A file for a new detector is most easily created by copying and editing an old file, using the commented column headings as a template.

The features of the detector file are as follows:

2.1.1 Title Record: the first two characters will be used as part of an output "mole name" to signify telescope number. The remainder of the record is a descriptive title that appears on all calculated output from all 11/70 programs based on this file. Additional data (range/energy version and file name) are later appended to the title, beginning in column 58.

2.1.2 Telescope Complexity: the number of modes (maximum 4) and gains (maximum 2). Modes for this double ended telescope will involve particles that stop after entering from either end and those that penetrate after entering either end. A single ended telescope like the ISEE-VLET, has only 1 mode.

2.1.3 Detector-Layer Records: one record for each distinguishable physical layer in the detector (maximum 19). These records include a 2 character element name and number for each electrically defined active element (maximum 8) or blank and zero for dead layers Threshold energies are also specified (MeV) in high and low gain for active elements. Every layer is defined by a thickness, spacing to the next layer and radius, all in microns, and a curvature index for curved elements. Thicknesses need not be integers. Columns 4,5 and 6 contain pointers that define how the signal (the energy deposited in each layer) will be summed by pointing to a summing register for each mode. (An attempt is made to duplicate the preamplifier-summing amplifier-PHA configuration of a HET). Registers number 1 and 2 will become the two "delta E" elements. Both must exceed threshold to form a coincidence. Register 6 sums the anti-coincidence signal, distinguishing stopping and penetrating particles. Energy deposited in registers 3, 4 and 5 will be converted to channels and then summed to produce the "E" pulse height. Register 7 collects the unobserved energy from dead layers.

2.1.4 Calibration Records (11): specify the conversion from MeV to channels for the active layers described in comments on the right for low and high gain, respectively, via

delta E(channels) = (channels/FSMeV) * (delta E(MeV)) + OFFSET

2.1.5 Slant Descriminator Definiton: up to two slants may be defined in each stopping mode and for penetrating mode. Slants are computed in channels and, for a given mode, may apply to low gain only (GN=1) or both low and high gain (GN=2). Slants are computed from the listed coefficients by

CH1 * delta E1 + CH2 * delta E2 + CH3 * E + SUM

where delta E1, delta E2 and E are expressed in channels. The slant is true if the above result is greater than zero. The text labels under 1, 2 or both will appear on the printed output whenever the corresponding slant conditions are true.

2.1.6 Species Cards: define the specific particle species, modes and gains for the current track calculation. A header record specifies the number of modes and the number of species in each gain. This is followed by species records with a 4-character name, and its charge and mass (AMU).

2.2 TESTA Calculations:

With access to a detector file, TESTA proceeds to calculate track data for each gain and species listed on the file. For each such case, the subroutine TABLE is invoked to generate a range/energy table that will be used for all detector modes requested.

2.2.1 Logic Summary:

For each detector model, the program first maps the detector by summing the thicknesses in the proper direction to determine the particle range to each physical boundary of the system from the first coincidence (elements 1 and 2), to the anti-coincidences (element 6) or to ionization minimum for penetrating particles. For the first interface with each active element, the range is then modified so that the energy deposited in the detector exceeds thresholds.

The program then calculates the detector response as the particle range is stepped in small increments from boundary to boundary. The stepping algorithm allows the step size to increase if the charge in the response in any channel is less than a user-specified precision between 1 and 10%.

Each range point also corresponds to a given depth in the detector when detector spacing data are included. The depth and detector radii define a maximum inclination angle and for flat detectors, the response of a particle at the maximum angle is calculated For curved detectors, the "extreme response" curve depends upon the curvature and a first order approximation for dEr detectors is internally generated by TESTA.

A geometry factor is also defined at each calculated depth. A two-concentric-element geometry factor is calculated using radii of the front detector (first detector with sum register pointer not equal to 7), and the current detector (or the last detector pointer not equal to 7). The geometry factor is calculated as shown in Figure 2 of the main document.

The calculation starts at the front of the telescope and proceeds to greater and greater depth. The geometry factor at a given depth is taken as the minimum of the current and preceding ones in order to compensate to first order for detectors with large-radius elements that do not define the geometry.

2.2.2 The Range-Energy relation:

Calibration of the ISEE and Voyager experiment response matrices requires an accurate description of the stopping process from about 20 keV/nucleon for Iron nuclei in the first channel of the VLET (very low energy telescope) through minimum ionization at 2.4 GeV/nucleon. At high energies the stopping process is well described by the BETHE-BLOCK formula. Modifications of their formula allow it to be extended down to energies where the particle captures the first few orbital electrons. At low energies where the binding of orbital elections is approximated by the Thomas-Fermi model, the electronic stopping power is approximately linear in velocity and a more complex but well described nuclear stopping power begins to dominate the energy loss process. (Lindhard Scharff and Schiott, 1963, "LSS")

At intermediate energies, where the stopping power is passing through a maximum, it is common to use empirical power law expansion to fit the measurements (eg. Northcliffe & Schilling 1970). In this work, we have preferred to modify the high and low energy forms into better agreement and to use an empirical weighting factor to shift between them in order to merge smoothly into the correct asymptotic behavior.

The Thomas-Fermi statistical model of the atom results in a smooth dependence on the atomic number of the particle and of the stopping material. A more discontinuous behavior arising from atomic shell effects has been observed (cf eg. Ziegler, 1978). We have included a small empirical correction term B(Z) in the expression for the characteristic velocity of each element to cover any residual effects of this kind. This factor is found to vary more smoothly than expected and to peak for Silicon ions (stopping in the Si detectors).

The available data for ions stopping in Si (or Al) have been considered in determining the fit constraints as well as data from the ISEE- VLET's which constrains the range energy for the heavier elements within an accuracy of 2-3%.

Parameters of the stopping material, Si, are explicitly included in the formalism as Z(stopping), A(stopping), the mean ionization potential, I(stopping) =173.5 eV and the density, ρ(stopping) = 2.33 g/cm^2. However the adequacy of the fit for other materials has not been studied and should not be assumed.

Our form of the BETHE-BLOCK expression with charge pickup differs slightly from that given in Bichsel (1970). Let b be the particle velocity (in units of the velocity of light,c) and Z and A be its atomic number and weight, respectively. Let

$$\beta_0 \equiv B(z)\,\frac{z^{2/3}}{137} \qquad (1)$$

characterize the particles' orbital electron velocity where B(Z) is a parameter of order 1 described previously and given by the table:

Z	B(Z)	Z	B(Z)	Z	B(Z)
1	.7	10	.99	19	.985
2	.8	11	.99	20	.985
3	.85	12	1.02	21	.985
4	.9	13	1.02	22	.985
5	.95	14	1.02	23	.995
6	.975	15	1.0	24	.995
7	.975	16	1.0	25	.995
8	.975	17	1.0	26	.995
9	.99	19	1.0	27	1.0

Using β_0, we define

$$v_{rel} = (\beta - 0.004)/\beta_0 \quad \text{for} \quad \beta > .004 \qquad (2)$$
$$= 0 \qquad\qquad \beta < .004$$

the .004 offset being empirical.

The effective charge for stopping, Z^*, is

$$Z^* = Z(1 - \exp(-v_{rel})) \qquad (3)$$

and our BETHE-BLOCK form is

$$\left.\frac{dE}{dx}\right|_{BB} = c_1 \frac{Z^{*2}}{\beta^2}\left[\ln\left(1 + \frac{2m_e}{I_a}\beta^2\gamma^2\right) - \beta^2\right] \qquad (4)$$

where m_e is the electron mass,

$$\gamma = (1-\beta^2)^{-1/2}$$

and the constant

$$c_1 = \frac{4\pi e^4 N_e}{m_e c^2}$$

$$= 3.071 \times 10^{-5} \frac{Z_a}{A_a} \rho_a \tag{5}$$

The latter value gives units of MeV/micron used in the programs. Including the one in the logarithm prevents a divergence at low velocities but has almost no effect in the region where the BETHE-BLOCK form dominates.

Generally speaking, the BB form will be valid for $\beta > \beta_0$ (see eqn. 1) and the LSS form will be valid for $\beta < \beta_0$. Since the transition appears in practice to depend on the electron characteristics of the target as well as the projectile, we define

$$c_{\beta 2} = \beta_0^2 + \frac{I_a}{2m_e} \tag{6}$$

The weighting factor is then

$$w_t = exp\left(-1.25\beta^2/c_{\beta 2}\right) \tag{7}$$

The LSS electronic stopping power (per atom) is given by

$$S_e = \xi_e \cdot 8\pi e^2 a_0 \frac{Z Z_a}{Z_{LS}} \frac{v}{v_0} \qquad \text{for } v > v_0 Z^{2/3} \tag{8}$$

where $\xi_e \sim Z^{1/6}$

and $Z_{LS}^{2/3} = Z^{2/3} + Z_a^{2/3}$

The following modifications are made to the LSS form:

1. A constant multiplier of 1.34 is included (other authors have also found Equation 8 to underestimate the stopping power).

2. A factor B(Z) is included in the denominator for consistency with Equation 1.

3. An exponential factor, similar in form to the weight factor

is included to roll over the linear dependence at and above the cross-over region.

The result, in MeV/micron is

$$\left.\frac{dE}{dx}\right|_{LSS} = 1.34 \cdot \frac{157.8\,\rho\, Z_\rho Z^{1.133}}{A_\rho (Z^{2/3} + Z_\rho^{2/3})^{3/2}\, B(Z)}\, \beta \exp\left(-0.5\, \beta^2 / c_{\beta 2}\right) \tag{9}$$

The contribution to the energy loss from nuclear collisions was obtained by fitting the Thomas-Fermi scattering function (see LSS figure 1) to the empirical form

$$f(x) = (.077)(\ln(4500x)) / (1 + 1.29x) \tag{10}$$

and integrating to obtain the dimensionless stopping power

$$\frac{d\epsilon}{d\rho} = \frac{1}{\epsilon}\int_0^{\epsilon} f(x)\, dx \tag{11}$$

which is a lengthy integration; retaining dominant terms gives (in our units)

$$\left.\frac{dE}{dx}\right|_{Nuc} = C_N \left\{ \left[8.157 + 0.5 \ln(w+1)\right] \frac{\ln(w+1)}{w} + \ln(w/w+1) - (1 + 0.645w)/(w+1)^2 \right\} \tag{12}$$

where

$$w = \text{MAX}\ (.007814\ ,\ C_\epsilon * E/A\ ) \tag{13}$$

in terms of the particle energy E, and the constants defined in equations 12 and 13 are

$$C_\epsilon = 1.29\, \frac{32566\, A A_\rho}{(A + A_\rho) Z Z_\rho (Z^{2/3} + Z_\rho^{2/3})^{1/2}} \tag{14}$$

and

$$C_N = 0.77\, \frac{0.511\,\rho\, A Z Z_\rho}{A_\rho (A + A_\rho)(Z^{2/3} + Z_\rho^{2/3})^{1/2}} \tag{15}$$

Finally, the full energy loss is defined to be

$$\frac{dE}{dx} = w_t \left.\frac{dE}{dx}\right|_{LSS} + (1 - w_t)\left.\frac{dE}{dx}\right|_{BB} + \left.\frac{dE}{dx}\right|_{Nuc} \tag{16}$$

In equation 16 the symbol | means that portion of the energy loss from the LSS type interaction, etc. for the other symbols.

The range-energy relation is derived from the energy loss via

$$R = \int_0^E \left(\frac{dE}{dx} \right)^{-1} dE \qquad (17)$$

using an algorithm described elsewhere.

The energy loss formalism described herein relates to programs and output described as version "R". Earlier (or later) versions may involve a completely different parameterization.

3. Operators guide

3.1 Input required:

In running TESTA, the run is prompted for:

- An output file name Any valid file name may be entered; ISEE convention uses a file type .TRK with names like ICHET1.TRK. The program may be terminated by entering a period instead of a file name.
- An input detector file name (e.g. ICHET1.DET)
- Stepping precision (percent channel change per step; default 5%)
- Print compression flag: true- print every line; false- print every other step for single mode telescopes, every 4th step for multi-mode telescopes. This controls printed output only, all steps are recorded on the track file.
- Range/energy flag: true- a one page complete range/energy loss table will be produced for each particle species in the detector file. A further prompt for new values of constants should be defaulted (/return); false- no R-E table output

3.2 Output Given:

The printed output from TESTA lists the telescope response for each step (depth) in the detector. Listed are:

- The range (depth) in microns
- The particle energy in MeV/AMU
- The response (channels)
- The response (channels)
- The response channels
- The name of a physical boundary when first encountered (XX for dead layers) These are the precise points at which the threshold is exceeded or the boundary is reached, not the nearest step.
- The name of the slant condition satisfied,if any
- The geometry factor (cm2 ster)
- The secant of the maximum inclination angle
- The energy and channel response for the extreme-response track at the same depth (three sets of entries)

The direct-access output file records contain similar information to that printed. The file is headed by index records for each species that point to the data records for each mode.