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Identification of Ultra Heavy Cosmic Ray Ions Recorded in Polycarbonate Detectors Using a Corrected Bethe–Bloch Formula

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Abstract

The Ultra Heavy Cosmic Ray Experiment (UHCRE) has recorded cosmic ray ions with $Z \geq 65$ in Earth orbit using polycarbonate detectors. The Restricted Energy Loss (REL) track formation model assumes that only the energy deposition due to distant collisions of the incident ion with the absorber atoms contributes effectively to track formation. This energy deposition is governed by the well-known Bethe-Bloch expression, which range of applicability can be extended by adding several terms, thus obtaining a "corrected" Bethe–Bloch formula. It has been found that the Mott correction, the relativistic Bloch correction, and the density effect are relevant for energy loss calculations, and therefore for charge identification, of fast ions with charge $Z \geq 65$ passing through polycarbonate track detectors. Calibration of the detectors is performed from accelerator exposures, taking into account the "corrected" formula, for identifying the charge of the ions recorded in the UHCRE.

1 Introduction:

The main purpose of the Ultra Heavy Cosmic Ray Experiment (UHCRE), in which result analysis our group participates, is to determine the elemental abundances of ions with $Z \geq 65$ present in cosmic rays (Domingo *et al*., 1996). It is necessary to achieve high-resolution charge measurements in order to determine the relative contribution of the *r* and *s* processes to nucleosynthesis and to derive the appropriate astrophysical conclusions.

The knowledge of the physical process of energy deposition by the incident particles in the track detectors and of the relationship between the response of the detector and this energy deposition is essential in order to attain precise and reliable results in the work developed. In particular, it is of great importance to characterize fully the particle registration process that takes place into the detector if we intend to identify the charge of unknown ions. Energy losses and ranges of charged massive particles are commonly calculated by using the Bethe–Bloch formula (Fano, 1963; Northcliffe, 1963) (hereinafter, uncorrected Bethe–Bloch formula). In particular, this uncorrected formula is not fully applicable to fast ions with $Z \geq 30$ stopping in a non-gaseous absorber, and it is necessary to introduce several corrections, thus obtaining a corrected Bethe–Bloch formula, in order to extend its range of applicability to a wider range of ion charges and energies and of absorbers (Ahlen, 1980, 1982; Waddington *et al*., 1986; Geissel *et al*., 1982; Leung, 1989). Our group has already studied the effect of such corrections on the determination of ranges and energy loses of swift heavy ions recorded on plastic track detectors (Domingo *et al*., 1989; Mompart *et al*., 1996), together with its possible influence on assignment of charges to the ions recorded in the UHCRE if calibration is performed from the knowledge that the most abundant UH ions recorded should correspond to the lead ($Z = 78$) and platinum ($Z = 82$) peaks (Domingo *et al*., 1998).

In the present work, we study the influence of taking into consideration the corrections to the Bethe–Bloch formula on the process of charge assignment. In particular, we have used the Restricted Energy Loss (REL) track formation model for relating the signal strength (S_S) recorded in the detector with the energy loss of the incident ion (Font, 1994; Domingo *et al*., 1996). We are interested on studying, from accelerator calibration of the detectors exposed to ions of known charges and kinetic energies, how to parameterize the relationship between S_S and REL for identifying the charge of the ions recorded in the UHCRE.

2 Energy Loss and REL Calculation:

The uncorrected Bethe–Bloch formula that we have used in the work performed in our group is (Mompart *et al*., 1996)

$$-\frac{dE}{d\xi} = 4\pi \frac{Ne^4}{m_e c^2} \frac{Z_1^2}{\beta^2} \frac{Z_2}{A} \left[\mathbf{ln}\left(\frac{2m_e c^2}{I} \frac{\beta^2}{1-\beta^2} \right) - \beta^2 + \psi(1) - \mathbf{Re}\,\psi(1+i\nu) \right]$$

where $-dE/d\xi$ is the average energy lost by the particle in the absorber per unit of mass thickness (with $\xi = \rho\,\boldsymbol{x}$, being ρ the absorber density and x the path length of the incident ion, thus $-dE/d\xi = (1/\rho)(-dE/dx)$); N is the Avogadro number; e is the electric charge of the electron, m_e is its rest mass; Z_1 is the electric charge of the incident particle in units of the electron charge, β is its velocity in units of the speed of light c; Z_2 is the atomic number of the absorber, A is its atomic mass; I is the mean excitation energy of the atomic electrons; $\psi(1) - \mathbf{Re}\,\psi(1+i\nu)$ is the Bloch correction, with ψ the logarithmic derivative of the Euler Γ function $\left(\psi(z) \equiv d[\mathbf{ln}(\Gamma(z))]/dz\right)$ and $\nu \equiv Z_1\alpha/\beta$, being $\alpha = 1/137$ the structure constant of the electromagnetic coupling.

According to the Restricted Energy Loss (REL) track formation model (Benton & Henke, 1968; Benton & Nix, 1969), the formation of the latent track is due only to the energy deposited by the distant collisions of the incident particle with the absorber electrons. Distant collisions are defined as those with large impact parameter, which originate recoil electrons with low energy (ω), smaller than a fixed value (ω_0) that depends on the absorber, and which deposit their energy in the neighborhood of the incident particle path. The distant collisions contribution to the Bethe–Bloch formula gives the expression used to calculate the Restricted Energy Loss of any incident ion in a given absorber

$$-\left(\frac{dE}{d\xi}\right)_{\omega<\omega_0} \equiv \mathrm{REL}_{\omega_0} = 4\pi \frac{Ne^4}{m_e c^2} \frac{Z_{eff}^2}{\beta^2} \frac{Z_2}{A} \left\{ \frac{1}{2} \mathbf{ln}\left(\frac{2m_e c^2}{I_0^2} \frac{\beta^2}{1-\beta^2} \omega_0 \right) - \frac{\beta^2}{2} \right\}$$

where Z_{eff} is the incident particle effective charge, and I_0 is the mean ionization potential of the absorber. Given the difficulties of calculating theoretically ω_0, its value for a specific absorber is, in practice, obtained from the best fit to experimental data. When the process of deduction of this REL expression is analyzed, it turns out that the ½ factor which appears in the logarithm term inside the bracket of this equation, as well as the ½ factor in front of the subsequent β^2 term, are due to the fact that only one half of such terms are originated by the contribution of distant collisions. Contrarily, the complete quantic Bloch term $\psi(1) - \mathbf{Re}\,\psi(1+i\nu)$ is due to close collisions and therefore should not appear at all in the Restricted Energy Loss term.

When the approach utilized to deduce the Bethe–Bloch formula is changed for increasing its range of applicability to faster and heavier ions, as well as to dense absorbers, it is found that a new expression is obtained, with several corrections that must be added to the uncorrected expression (Waddington, 1986; Mompart *et al*., 1996)

$$-\frac{dE}{d\xi} = \frac{4\pi Ne^4}{m_e c^2} \frac{Z_{eff}^2}{\beta^2} \frac{Z_m}{A} \left[\mathbf{ln}\left(\frac{2m_e c^2}{I_m} \frac{\beta^2}{1-\beta^2} \right) - \beta^2 + B - S - D + M + C_R - \Delta_R \right] \cdot F$$

where Z_m is the mean atomic number of the absorber; I_m is the adjusted ionization potential of the absorber; $B = \psi(1) - \mathbf{Re}\,\psi(1 + i\nu)$ is the quantic Bloch correction, that already appeared in the uncorrected expression; C_R is the relativistic Bloch correction, which should always be taken together with B; S is the inner shell correction, accounting for the finite velocities of the absorber electrons; D is the density effect correction, which appears due to the absorber polarization; M is the Mott correction, due to considering the Mott cross section instead of the Rutherford one; Δ_R is the Leung correction, that takes into account the relativistic motion of the inner shell electrons of high Z_2 absorbers; and F is the low velocity correction, which, according to Waddington *et al.* (1986) should not be considered if the incident ion effective charge is used, as both seem to account for the same physical process. Strictly speaking, this expression should, in addition, be multiplied by an extra factor, which sometimes is referred to as ultrarelativistic correction, which accounts for the energy loss by bremmstrahlung.

The next step is to find out which, if any, of the terms added for correcting the energy loss expression contribute to track formation. Although it seems clear that only those terms related to distant collision contributions are relevant, one must remember that the separation between close and distant collisions is somehow artificial and there is not a clear boundary among them. Some terms may, in addition, have contributions from both kinds of collisions, which might not be possible to separate. As a first approximation, the Bloch and relativistic Bloch corrections, together with the Mott and Leung corrections are due to close collision contributions, so they should not contribute to REL and, therefore, to track formation. The density correction, due to distant collisions, together with the inner shell correction and the low velocity correction, due to both close and distant collisions, may contribute to some extent to REL. Nevertheless, the contribution of the inner shell correction S and that of the Leung correction Δ_R are not considered in our work as they are negligible for swift heavy ions losing energy in an absorber such as a plastic track detector (Domingo *et al.*, 1998). The low velocity correction is not taken into consideration (we consider the effective charge of the incident ion) and the energy deposition by bremmstrahlung does not contribute to track formation.

According to (Domingo *et al.*, 1998), we have considered that the contribution to REL of the processes involving close collisions is not exactly zero, but that they have a partial contribution to REL and, therefore, to track formation. This partial contribution is accounted for by a “close collisions contribution” (*ccc*) parameter, ranging from 0 to 1, which multiplies the contribution of all close collision terms to REL.

$$REL_{\omega_0} = \frac{4\pi N e^4}{m_e c^2} \frac{Z_{eff}^2}{\beta^2} \frac{Z_m}{A} \left[\frac{1}{2} \mathbf{ln} \left(\frac{2 m_e c^2}{I_m^2} \frac{\beta^2 \omega_0}{1-\beta^2} \right) - \frac{\beta^2}{2} - D + \left(M + B + C_R \right) \cdot ccc \right]$$

3 Experimental Procedure and Results:

Calibration of the detectors has been performed from measurements in polycarbonate plastic track detector stacks exposed at the Berkeley Bevalac to U, Au and La ions of kinetic energy ~1GeV/n. According to the REL track formation model, the relationship between the signal strength S_S and REL can be written as

$$S_S = g\left(\mathrm{REL}_{\omega_0}\right)^h$$

REL_{ω_0} is related to the kinetic energy of the incident ion which, in turn, is related to is residual range R. As the stack thickness is such that all incident ions stop inside the detector, several measurements of (S_S, R) couples can be performed along the track of any given incident ion of known charge. From this set of measurements, the calibration procedure allows determining the values of the g and h parameters, as well as the “close collisions contribution” *ccc* value. When the results are analyzed, it is found that the contribution of close collisions, if existing, should be small. Values of *ccc* greater than 0.4 lead to unrealistic assignments of the charge scale of the ions recorded. It is also found that, although there no significant differences in the overall charge assignment of the ions recorded when the "corrected" REL expression is used instead of the "uncorrected" one, the charge uncertainty associated to the process of charge assignment decreases. The values of the *g*, *h* and *ccc* parameters obtained from this accelerator calibration will be used to identify the charge of the UH ions recorded in the UHCRE, and to discern weather this methodology improves the results presented in (Domingo *et al*., 1998) from the knowledge of the most abundant UH peaks.

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