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ESTIMATION OF CHARGE OF HEAVY COSMIC–RAY PARTICLES USING THE δ–RAY COUNTING METHOD IN FUJI ET–7B NUCLEAR EMULSION

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The range distribution of δ–rays produced by heavy nuclei of energy ≈ 5 GeV/n in Fuji ET–7B nuclear emulsion has been investigated using data from an exposure to primary cosmic rays in a balloon–borne plastic–emulsion chamber. The estimated δ–ray densities per 100 μm for projectiles of charges $Z = 14$, 20 and 26 are in accord with the low–range simulation results of Ichimura et al.

1. Introduction

The charges of projectiles detected in the CR-39 plastic detector can be confirmed by counting of δ–ray tracks in the adjacent nuclear emulsion in balloon-borne plastic-emulsion chambers. The charge number of heavy projectiles can be determined by the plastic detectors using the track etch technique [1] and from the linear density of δ–rays ejected by the particle in the nuclear emulsion. Biswas et al. [2] have followed a similar counting of δ–ray density by considering δ–ray tracks with four or more grains. The long–range convention has also been used, for the higher

δ–ray density simulation. They have used Ilford G–5 emulsion and related δ–ray density per 100 μm (N_δ) to the kinetic energy for various charges up to $Z = 13$ by measuring δ–ray density of respective tracks. Recently Kawamura et al. [3] have identified cosmic ray projectiles in a balloon borne plastic–emulsion chamber with the help of sensitive materials like CR-39 (HCB 0.5%) plastics and Fuji ET-7B nuclear emulsions. They specified charges of heavy primaries for Z $\leq$ 10 from counting of δ–ray tracks in nuclear emulsions and also from the etch pit calibration in CR-39 (HCB) plastics satisfactorily (charge resolution $\sigma(Z) \approx 0.5e$). They found a fair correlation between the average number of δ–rays per 100 μm in Fuji ET-7B emulsion and the reduced etch rate distribution for heavy ions detected in CR-39 (HCB) plastics. This fact is also supported by our recent investigation with the same type of track detectors [1].

More recently, Ichimura et al. [4] have developed a δ–ray simulation programme to predict the detected charge of heavy cosmic ray primaries accurately, as observed using a charge–coupled–device microscope for the evaluation of the range distribution of δ–rays in Fuji ET-7B emulsion.

In the present work we have determined the range distribution of low energy ($>$ 15 keV) δ–rays produced by cosmic ray projectiles Si, Ca and Fe of about 5 GeV/n in Fuji ET-7B nuclear emulsions available from a plastic–emulsion chamber of a balloon flight experiment. Attention has been paid to relate the number of the δ–rays per 100 μm for different projectiles with the δ–ray cut–off ranges. The present result at lower δ–ray cut-off range has been compared with the δ–ray range distribution results of Ichimura et al. [4].

2. *Experiment*

The balloon–borne plastic–emulsion chamber (consisting of CR-39 (HCB) plastic and Fuji nuclear emulsion) was exposed to primary cosmic rays over Alice Springs for 32 hours at an atmospheric depth of 9.8 g cm^{-2}. The top stack of the chamber, that we have analysed in the present work, was composed of 5 sheets of CR-39(HCB 0.5%), each of thickness $\approx$ 1600 μm, placed on 4 sheets of nuclear emulsion of Fuji ET-7B type with 50 μm emulsion coated on both sides. The chamber was designed in such a way that the cosmic nuclei could penetrate the plastic sheets first and then pass through the horizontally placed emulsion sheets.

The damage trail in the polymer formed by a cosmic nucleus comes out as cone shaped hole with elliptical surface openings, after the recovered plastic detectors were treated in a 7.5N NaOH solution at $(80 \pm 0.1)^\circ$C for 96 hours (4 days). The long etching time was adopted to raise the charge detection threshold to $Z \geq 10$, which is $Z \geq 6$ for conventional (1 day) etching of CR-39. Since we are interested only in the heavy ion spectrum (Z = 10 to 28), the higher threshold helps to eliminate the lighter ($Z = 6$ to 9) components.

The major (D_A) and minor (D_B) axes of each elliptical surface mouth have been measured under a total magnification of $\times$120 using a Zeiss Winkel binocular optical microscope. The response parameter of the detector, more commonly known as reduced etch rate $(V_T/V_G - 1)$, was calculated using the formula [5]:

$$\frac{V_T}{V_G} - 1 = \sqrt{1 + \frac{4\left(D_A/2H\right)^2}{\left[1 - \left(D_B/2H\right)^2\right]^2}}. \quad (1)$$

The reduced etch rate distribution of 2968 pits is shown in Fig. 1. It shows distinct peaks in the charge range $Z = 10$ to 28.

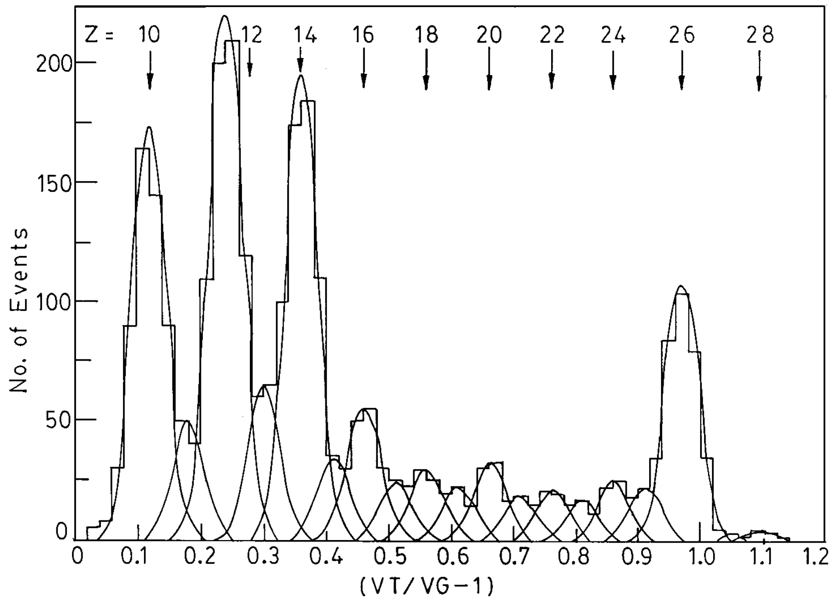

Fig. 1. Cosmic primary heavy nuclei detected in the CR-39 (HCB) detector as a function of reduced etch rate. Every charge peak is labelled with the corresponding charge. The peaks exhibit the heavy nuclei charge abundances at balloon altitude ≈ 32 km over Alice Springs.

The conventional δ–ray counting was carried out for tracks of even Z nuclei, viz. Ne ($Z = 10$), Mg ($Z = 12$), Si ($Z = 14$) up to Fe ($Z = 26$), by following respective tracks from the plastic (CR-39) sheet to the adjacent emulsion sheet. Since the emulsion and CR-39(HCB-0.5%) plates are all of the same size (20 cm × 25 cm), it was easy to follow the tracks by matching the coordinates on the microscope stage. After matching the coordinates, the length of the heavy tracks were measured under a ×100 oil immersion objective along with a ×12 occular eyepiece with a least count of 1.335 μm and shrinkage factor 2.6. The average energies of the very heavy primaries were estimated from the distribution of the opening angles of α–fragments in emulsion and found to be 5.01 GeV/n [1].

3. Results and discussion

When a heavy nucleus penetrates an emulsion sheet, the electrons or δ–rays are ejected from atoms along the path in the emulsion. Counting of δ–rays allows the determination of the projectile charge without knowing the specific energy loss in matter. The number of δ–rays with energy between E_{min} and E_{max}, ejected per unit length along the heavy track, is related to the charge number by the following conventional relation used earlier by Powell et al. [6]

$$n_{\delta_{theor}} = 2\pi n_e \left(\frac{e^2}{m_e c^2}\right)^2 \left(\frac{m_e c^2}{E_{min}} - \frac{m_e c^2}{E_{max}}\right) \frac{Z^2}{\beta^2}, \tag{2}$$

where n_e is the number of electrons per unit volume in the material, Ze is the projectile charge, βc is the velocity of the projectile and m_e is the electron mass.

The average number of δ–rays per unit length and of energy in the energy range E_{min} to E_{max}, $< n_\delta >$, can be estimated from the following relation [4]:

$$< n_\delta >= 2\pi n_e r_0^2 \frac{m_e}{E_0} F\left(\sqrt{\frac{E_c}{2m_e}}\frac{1}{\beta\gamma}\right)\Big|_{E_{min}}^{E_{max}} \cdot \frac{Z^2}{\beta^2}, \tag{3}$$

where $n_e = 1.027 \times 10^{24}$ electrons/cm^3, r_0 is the classical electron radius, $\gamma = (1-\beta^2)^{-1/2}$ and

$$F(x) = 1 + 2\beta^2 x^2 \ln x + 2\pi\alpha Z\beta x(1 + x\ln x).$$

The numerical values concerning the energy–track density relation of δ–rays in Fuji ET-7B emulsion have been taken from Ichimura et al. [4]. The terms $E_{max} = 2m_e\beta^2\gamma^2$ and E_{min} are the energies corresponding to the maximum and minimum ranges of the δ–rays in emulsions. The conventional energy loss rate of an electron per unit length, passing with velocity βc through matter with the ionization potential $I(Z)$, is given by the Bethe formula [7]

$$-\left(\frac{\Delta E_e}{\Delta L}\right)_{Bethe} = 2\pi n_e r_0^2 \frac{m_e}{\beta_e^2}\left\{\ln\left[\left(\frac{E_e}{I}\right)^2 \frac{\gamma_e+1}{2}\right] + \frac{1-(2\gamma_e-1)\ln 2}{\gamma_e^2} + \frac{(\gamma_e-1)^2}{8\gamma_e^2}\right\}, \tag{4}$$

with $E_e = m_e(\gamma_e - 1)$.

Ichimura et al. [4] have used the following modified form for calculation of energy loss rate in the low energy region

$$-\frac{\Delta E_e}{\Delta L} = \left[1 - \frac{1}{1+(\beta_e/\beta_0)^3}\right] - \left(\frac{-\Delta E_e}{\Delta L}\right)_{Bethe}, \tag{5}$$

where $\beta_0 = 0.08$ and $< I >= 280.5$ eV for Fuji ET-7B type.

The mean path length, L_δ, of a δ–ray from the point of production to the end point in the emulsion can be estimated from

$$L_\delta = \int_0^{E_0} \frac{\mathrm{d}E_e}{\left(\frac{-\Delta E_e}{\Delta L}\right)}, \tag{6}$$

where E_0 is the initial energy of δ–ray.

The mean path length (L_δ) vs. initial energy (E_0) curve given by Ichimura et al. [4] obtained from the above relation is displayed in Fig. 2. From the figure, one can convert the mean path length to the initial δ–ray energy.

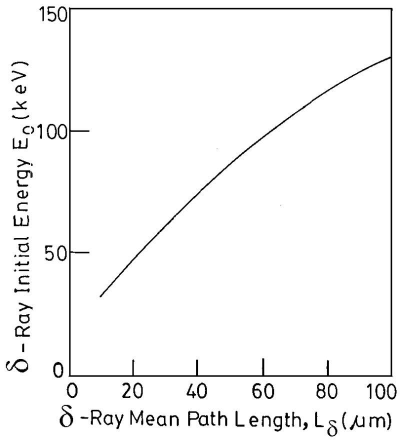

Fig. 2. Mean path lenth L_δ (10 μm–100 μm) plotted against the initial δ–ray energy E_0 for Fuji ET–7B emulsion, calculated from Eqs. (5) and (6).

The δ–rays density (N_δ) for cosmic nuclei with even Z values, viz. for $Z = 10$ to 26, has been counted in Fuji ET-7B nuclear emulsion, following the respective tracks from the adjacent plastic (CR-39 HCB 0.5%) detector. The following relation between the number of δ–rays per 100 μm (N_δ) and the corresponding Z/β value was found:

$$N_\delta = A\left(\frac{Z}{\beta}\right)^2 \tag{7}$$

where $A = 0.04 \pm 0.004$.

In Fig. 3, the δ–ray density for different Z/β values, according to equation (7), is plotted versus the respective reduced etch rate $(V_T/V_G - 1)$ value from Fig. 1. Figure 3 shows the correlation plot between the charge response of very heavy ions in plastic and emulsion detectors through the following form,

$$V_T/V_G - 1 = A + BN_\delta + CN_\delta^2 + DN_\delta^3, \tag{8}$$

where $A = -0.1447 \pm 0.095$, $B = 0.0767 \pm 0.002$, $C = -0.00212 \pm 0.0006$ and $D = 0.0000299 \pm 0.000008$.

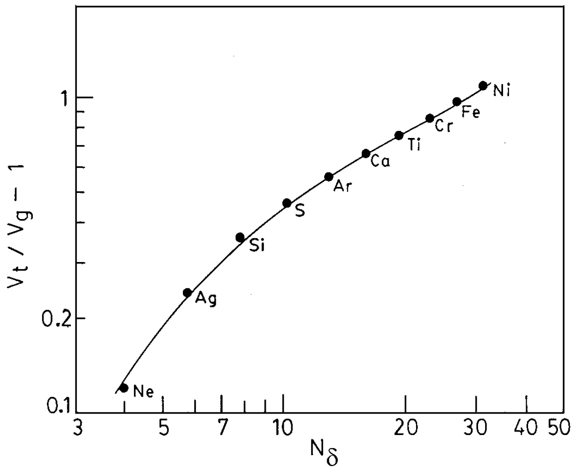

Fig. 3. Correlation between the number of δ–rays per 100 μm in Fuji emulsion and the reduced etch rate $(V_T/V_G) - 1$ in the adjacent CR-39 (HCB 0.5%) track detector for different primary projectile charges at energy ≈ 5 GeV/n.

Figure 4 shows the range distribution of δ–rays emitted by three different (Si, Ca, Fe) heavy cosmic nuclei incident on the emulsion, observed by Ichimura et al. [4], along with those values obtained from our experiment at 5 GeV/n. This is the energy of the incident nuclei at depth of observation as measured by opening angle method in the emulsion [1]. The ordinate in Fig. 4 represents the number of δ–rays per 100 μm multiplied by $(\beta/Z)^2$. It is plotted as a function of range distribution of δ–rays, $|Y|$, in μm. Here we present our results for Si, Ca and Fe nuclei with δ–rays of ranges ≥ 4.44 μm. Full curve in Fig. 4 shows the least squares fit to the data that follows the relation:

$$\frac{\beta^2}{Z^2} N_\delta = A \exp(-B|Y|). \tag{9}$$

where $A = 0.0488 \pm 0.004$ and $B = 0.0785 \pm 0.004$.

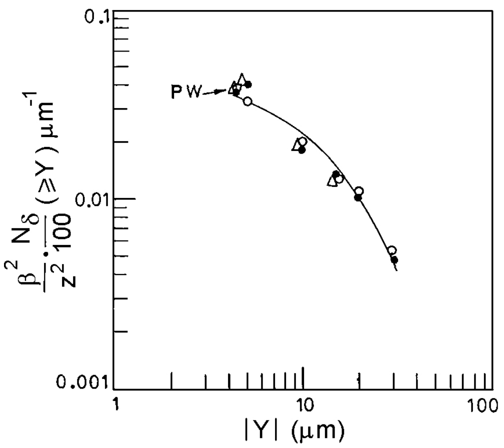

Fig. 4. Range distribution of $|Y|$ for δ–rays ejected by Si *($\triangle$),* Ca *($\circ$) and* Fe *($\bullet$) projectiles in Fuji ET-7B emulsion. Experimental data for δ–rays of ranges greater than the cut–off values of 4.70* μm, *9.7* μm, *15.0* μm, *19.7* μm *and 29.6* μm *(Ref. 4) and for δ–rays of ranges* > 4.44 *μm. Full curves show the least square fits to data after relation (9).*

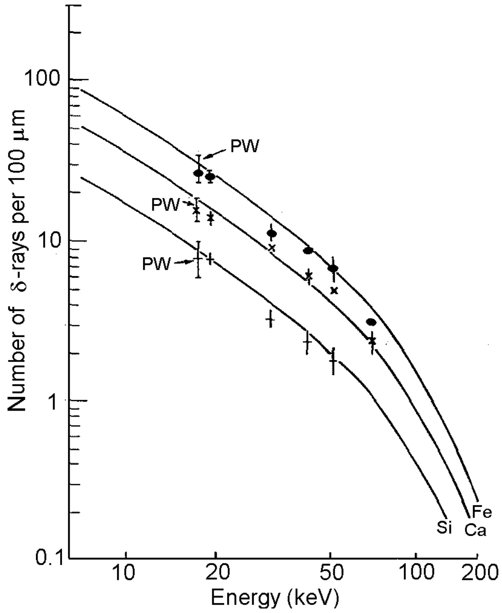

Fig. 5. Plot of density of δ–rays versus the energy cut–off value, for δ–rays ejected by Si *(+),* Ca *(x) and* Fe *($\bullet$) nuclei, for δ–ray energy ranges above the cut-off values of 19.0* keV, *30.7* keV, *41.01* keV, *50.0* keV *and 70.8* keV *(Ichimura et al. [4]), and above* 15 keV *(present work). Full lines show the simulation results after Ichimura et al. [4] for maximum δ–ray energy transfer of 400* keV.

From the range–energy plot (Fig. 2), the energy corresponding to the cut-off range 4.44 μm in the present case is found to be 15 keV. So the present result on δ–ray density (obtained from Eq. (7)) above 15 keV is shown in Fig. 5 along with earlier experimental results [4] for Si, Ca, Fe projectiles in ranges 20 to 70 keV.

4. *Conclusions*

The present experimental δ–ray density distribution data at energies > 15 keV have been compared with the theoretical simulation calculations results of Ichimura et al. [4]. Our study indicates that the theoretical δ–ray distribution results obtained from simulation can be extrapolated down to δ–ray cut–off energy of 15 keV and are compatible with the present experimental N_δ data for Si, Ca and Fe projectiles.

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ODREĐIVANJE NABOJA TEŠKIH ČESTICA KOZMIČKOG ZRAČENJA POMOĆU BROJANJA δ–ZRAKA U FUJI ET–7B NUKLEARNOJ EMULZIJI

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Eksperimentalni podaci o raspodjeli gustoće δ–zraka na energijama iznad 15 keV uspoređeni su s rezultatima simulacijskog programa koji je razvio Ichimura sa suradnicima za čestice sa $Z = 14$, 20 i 26.