Indian J. Phys. **64A** (3) 175-181 (1990)

Cosmic ray propagation studies from sub-iron and iron abundances in Spacelab-3 Anuradha experiment

N Durgaprasad, S Biswas, B Mitra, R K Singh and M N Vahia
Tata Institute of Fundamental Research, Colaba, Bombay-400 005, India
and
A Dutta and J N Goswami
Physical Research Laboratory, Ahmedabad-380 009, India

Abstract : Solid state nuclear track detectors such as CR-39 and Lexan Polycarbonate, have been used here to study the properties of low energy cosmic rays. Especially study of the low energy region (namely 30 – 100 MeV/amu), not hitherto easily accessible for other types of detectors and for iron group nuclei, was made possible in this work, by flying these plastics in space vehicles outside the earth's atmosphere. The instrument Anuradha flown in Spacelab-3 space shuttle was employed for this purpose. An enhanced ratio of 1.1 ± 0.3 was observed for the ratio of (scandium to chromium) to iron nuclei in 50-100 MeV/amu region. Nonstandard models of propagation of iron group nuclei in space including reacceleration process would be needed for explaining the observed data.

Keywords : Cosmic rays, Anuradha experiment, iron group nuclei.

PACS Nos : 94.40. - i, 94.80. +g

1. Introduction

Over the past few years, solid state nuclear track detectors (SSNTD) were found to be extremely useful in the study of low energy cosmic rays ($E \leqslant 100$ MeV/amu). Of especial importance is the most sensitive plastic CR-39 capable of detecting and measuring charge (Z) and energy (E) of particles $Z/\beta \geqslant 6$ where β is the velocity of the particle with respect to light. Such a plastic was flown in Anuradha Spacelab-3 in 1985. The aim of the work reported in this paper is to measure the charge ($Z \geqslant 21$) and energy ($E = 50 - 100$ MeV/amu) of iron group nuclei. Plastics exposed in satellites to outer space have a unique advantage in this regard as compared to electronic detectors flown in balloons, rockets and satellites. We report in the succeeding pages the experimental details of the methods used and the results obtained. Our previous Skylab experiment using Lexan detectors yielded a significantly large value for the ratio of iron secondaries (Sc – Cr) to iron (Fe – Co) in 50 – 150 MeV/amu (Durgaprasad and Biswas 1988). We measured again this ratio in this experiment and discussed its significance.

2. The experimental procedure

The Anuradha instrument was flown on board the space shuttle Spacelab-3 on a six day mission in 1985 at an altitude of 350 km and with an orbital inclination of 57° to the equator. The solar activity was approaching solar minimum during this period. The instrument consisted of two stacks of circular plastic sheets of dimensions 40 cm diameter, the top stack being stationary and the bottom one of 149 CR-39 sheets rotating slowly. The rotation was used to get the time resolution, the advantage of which had been used in the succeeding investigation reported by Mitra *et al* (1990). The present investigation was aimed to study primary and secondary iron group nuclei. Even though relativistic iron nuclei can be recorded in CR-39 sheets, only particles below the energy 400 MeV/amu can be brought to rest in the 4.5 cm thick stack of 149 sheets. We have studied at present, particles that stop within the stack and have energy less than 100 MeV/amu, as a first attempt. In later attempts this energy will be extended to 400 MeV/amu by studying lower layers of the bottom stack. The region of energy 50 – 100 MeV/amu is scantily studied so far.

The experimental procedure adopted is as follows. First the CR-39 and Lexan sheets were etched in a solution of 6.25 N NaOH for six hours at 70°C. After drying they were cut into four quarters. These sheets were later mounted on perspex pieces and scanned for cones in the Leitz Ortholux microscopes. An area of 337 cm² in sheet 1 – 2 was scanned so far. These cones were later followed from sheet to sheet till they left the twentieth sheet and only those particles that stopped in these sheets were measured. From these measurements the values of V_t/V_g (= C.L./B, where V_t is the track etch rate, V_g the bulk etch rate, C.L. is the cone length and B is the bulk material removed since t_0 the etch starting time) were calculated using the relations first obtained by Henke and Benton (1971) and as was obtained by us previously (see for example, Vijayadamodar and Durgaprasad 1988). In this paper, was also described the procedure adopted for determining the charge (Z) and energy (E) of these particles. The charge calibration was done using the beams of 140 MeV/amu iron nuclei to which the stacks were exposed, and stopped in the 16 – 18 sheets depending on dip angle and the thickness of the sheet, at that point. From Z and E values, the fluences (F) and the abundances related to iron were determined using the procedure adopted by us previously (see for example Durgaprasad and Biswas 1988).

3. Results and discussion

We restrict in this work a study of particles of charge greater than calcium and less than cobalt and estimate the Sc – Cr/Fe – Co ratios in cosmic rays. This ratio is a sensitive indicator of the propagation history of cosmic ray heavy nuclei in the galaxy. This is because the Sc – Cr particles are supposed to be rare in the sources and results in cosmic rays due to their traversal of matter in the source regions and interstellar space. The results on the carbon to calcium nuclei will be discussed elsewhere (Mitra *et al* 1990).

The histogram of about ninety nuclei obtained from the present data is given in Figure 1. It should be noted that the data do not represent equi-energy intervals scanned for all the ions, as the response function for nuclei is not the same. This response increases rapidly with atomic number. That is why we found more iron nuclei and less secondaries, whereas in reality it is much more. At this energy

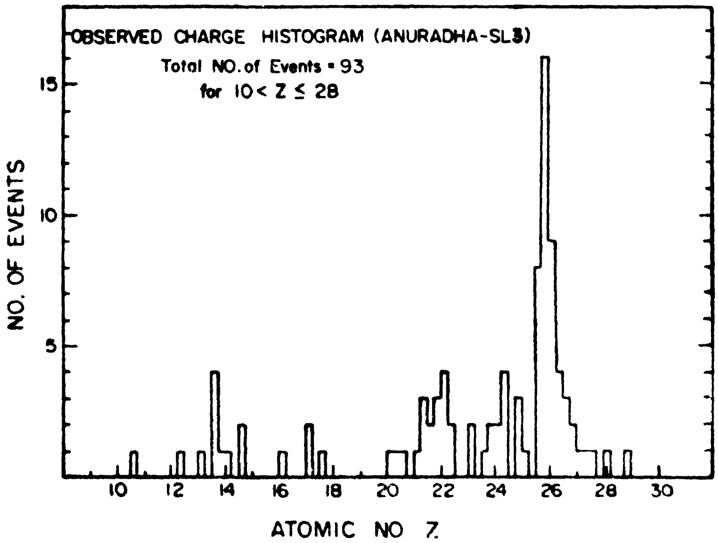

Figure 1. The measured charge spectrum of 93 observed nuclei. The relative numbers do not reflect their relative abundances since the energy intervals of observation are not the same.

range of 50 – 100 MeV/amu, direct access for fully stripped iron group nuclei of galactic cosmic rays is possible in the high latitude segments of the Spacelab-3 orbit. Anomalous cosmic rays come either from the heliosphere or local interstellar space. They are likely to be not included in the sample since they traverse little matter and are not likely to produce secondaries.

From this data, the sub-iron ($Z = 21 - 24$) to iron ($Z = 26 - 27$) ratio was obtained as follows :

We used two methods of obtaining this ratio. Both gave almost the same result, we now outline below these two methods.

3.1. Method I : In the first method, we calculate the maximum and minimum energies (from the computed ranges) of the titanium, chromium and iron nuclei, that are recorded in this stack. From this, the flux ratio, r, is defined

$$r = N(21-24)/N(26-27)$$
$$= (1/N[26-27])*[N(21-22)*(\Delta E(26)/\Delta E(22))$$
$$+ N(23-24)*(\Delta E(26)/\Delta E(24)] \quad (1)$$

where $N(Z)$ denotes the number of observed nuclei of charge Z. In the above equation $\Delta E(Z)$ is taken as $[E \max (Z) - E \min (Z)]$. The minimum energy E (min) is calculated from the minimum range (R min) as

$$R\,(\min) = [t(\mathrm{Al+mylar}) + t(1-1) + t(1-2)]/\sin\delta$$
$$= (182+337+235)/\sin 40^{\circ} = 1173\ \mu\mathrm{m} \quad (2)$$

where $t(N)$ is the thickness of the sheet N, δ is the average dip angle of the tracks taken in this investigation as 40 degrees. The value of R (min) turns out to be 1173 μm. From this E (min) is calculated using the range energy relation of Henke and Benton (1971).

The minimum recordable etch rate ratio V_t/V_g is taken as 2.5 in the top sheet 1–2 at top surface. The residual range corresponding to this etch rate ratio is obtained from V_t/V_g versus RR. Let us call this value as $R_e(Z)$. Then R (max) (Z) is computed from the relation

$$R\,(\max)\,(Z) = R\,(\min)\,(Z) + R_e\,(Z) \quad (3)$$

E (max) (Z) is obtained from R (max) (Z) and thus also $\Delta E(Z)$.

N(Z) is the actual number of observed nuclei and are taken from the experimental data. Then using eq. (1), the ratio r is calculated. These values of R (min) (Z), R (max) (Z) and $\Delta E(Z)$ are given in Table 1.

Table I. Values of ΔE, MeV/amu obtained from method 1.

Z	V_t/V_g	R_e (Z) (μm)	R_{max} (Z) (μm)	R_{min} (Z) (μm)	E_{max} (Z) (MeV/amu)	E_{min} (Z) (MeV/amu)	ΔE (Z) (MeV/amu)
22	2.5	2400	3573	1173	73.3	39.3	34.0
24	2.5	3200	4373	1173	86.2	41.2	45.0
26	2.5	4000	5173	1173	99.0	43.1	55.9

3.2. Method 2 : In the second method, ΔE (Z) is calculated from the actually observed values of E (min) (Z) and E (max) (Z) in the experimental sample and ΔE is also calculated. The rest of procedure followed is same. In Table 2 are given these values. In Table 3 are given the values of the relative abundances of the nuclei [$Z = (21-27)$] obtained by both the methods.

The observed ratio was 1.1 $\pm$ 0.3 for Sc–Cr/Fe–Co particles. It will be noted that a similar high value for sub-iron to iron abundance ratio at low energy was also observed in the Skylab experiment (Biswas et al 1975, Durgaprasad and Biswas 1988).

Table 2. Values of ΔE MeV/amu obtained from method 2.

Z	Observed values of E_{min} (MeV/amu)	Observed values of E_{max} (MeV/amu)	ΔE (MeV/amu)
22	51	78	27
24	55	89	34
26	55	97	42

In Figure 2, we give the variation of this ratio as a functional energy. In this figure, the results from other experiments at higher energies are included. These experiments were conducted with various kinds of detectors flown in balloons and satellites (HEAO-C2 for high energy and IMP 7 and 8 for low energy). It shows a strong energy dependence of path length traversed by cosmic rays. However, it should be mentioned here, that data of Garcia-Munoz et al (1987) were measured in a large energy interval of 87–400 MeV/amu. In Figure 2, curve 1 is based on

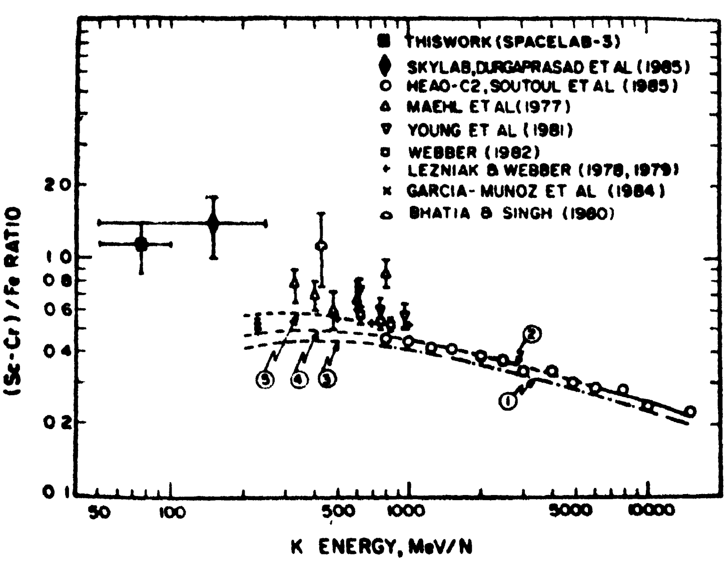

Figure 2. Observed ratios of $Z=21-24/Z=26-27$ nuclei as a function of their kinetic energy (MeV/amu). The computed curves from theoretical models are also shown (see text for details).

the fit obtained by Soutoul et al (1985) for B/C+O ratios. The mean escape path length is varied with energy as follows :

$$\lambda\ esc=\lambda b^{*}\beta^{*}R^{-6} \quad (R > 5.5\ GV) \tag{4}$$

$$\lambda\ esc=\lambda b^{*}\beta^{*}5.5^{-6} \quad (R < 5.5\ GV) \tag{5}$$

where R and β are interstellar values of the rigidity and velocity relative to that of the light. They find that $\lambda b = 24$ g/cm² and $\delta = 0.65$ for a fit at high energies (1 – 15 GeV/amu) for the ratio B/C+O. Curve 2 is based on the values of escape length (Soutoul *et al* 1985) as given below

$$\lambda\, esc = \lambda f \cdot \beta \cdot (1 + 0.4/Ekin)^{*} R^{-\delta} \quad (R > 5.5 \text{ GV}) \tag{6}$$

$$\lambda\, esc = \lambda f \cdot \beta \cdot (1 + 0.4/Ekin)^{*} 5.5^{-\delta} \quad (R < 5.5 \text{ GV}) \tag{7}$$

Table 3. The relative abundances of sub-iron ($Z = 21 - 24$) to iron ($Z = 26 - 27$) nuclei.

Charge of nuclei Z	Observed number of nuclei N	Method 1 Ratio relative to			Method 2 Ratio relative to		
		$Z=26$	$Z=26-27$	$Z=25-27$	$Z=26$	$Z=26-27$	$Z=25-27$
21 - 22	16	0.80	0.75	0.67	0.75	0.71	0.64
23 - 24	11	0.41	0.39	0.35	0.41	0.39	0.35
21 - 24	27	1.21	1.14	1.02	1.16	1.10	0.99
26	33	1.00	0.94	0.85	1.00	0.94	0.85
26 - 27	35	1.06	1.00	0.90	1.06	1.00	0.90
25 - 27	39	1.19	1.11	1.00	1.19	1.11	1.00

where Ekin is the interstellar kinetic energy in GeV/amu. The data agrees well at high energies ($E > 1$ GeV/amu) for values of $\lambda f = 26.8$ g/cm² and $\delta = 0.65$. Curve 3 is based on the expected ratios for the constant value of mean free path as 7 g/cm² in 200 – 1000 MeV/amu energy interval as deduced from B/C+O ratios. Curve 4 shows the ratios for a mean escape path length of 11 g/cm² for the same energy as deduced from high energies. Curve 5 is given for an infinite path length (complete confinement). The enhanced ratio observed in our experiment can not be understood in terms of the standard model of cosmic ray propagation. This suggests that iron group nuclei have different time history as compared to other nuclei. Non-standard models including reacceleration process or a two stage acceleration process would be needed for explaining the measured data. These models include large traversal of matter in the source region and adiabatic deceleration in the source such as during early phase of the expansion of the supernova remnant. Further work on these problems is continuing here.

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