The Role of Charge Changing Cross-Sections in Cosmic Ray Propagation

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Abstract

Variations of cosmic ray nuclear abundance at the top of the atmosphere is studied using different available partial cross-sections e.g. semi empirical formulations of Tsao et al., Garrard et al. and theoretical formulation of Wilson et al., based on the abrasion-ablation model. The Andersand Ebihara solar abundance is taken as a standard source spectrum in a Monte Carlo simulation of cosmic ray propagation through ISM. A Comparative study of the sub Fe/Fe ratios obtained using different cross-sections has been made.

1 Introduction:

Study of charge or mass composition of Cosmic Ray (CR) nuclear elements are necessary to test the validity of different models proposed for CR propagation through the interstellar medium (ISM). These models are basically formulated to understand the origin of cosmic rays and related nucleosynthesis processes.The nuclear abundances are measured either through satellites, balloons, or Earth based experiments. The observed abundances are mostly dominated by interstellar secondary production from cosmic nuclei traversing the ISM. CR nuclei can be broken up in collisions with interstellar hydrogen and this interaction will obviously involve the charge changing partial cross sections. So, these partial cross sections (pcs) have an important role in evaluating the source abundances.

Till date the available partial cross section formulations are mainly based on the experimental data collected using a variety of projectiles and targets at different energy ranges. But, there are controversies among the present cross section data or computer codes for partial cross sections, where some involves remarkable energy dependence of the projectile and some others are not. The cross section code of Tsao et al. (1993) is based on a semi empirical relation by Silberberg et al. (1990) and does not show adequate energy dependence. The other formulation by Wilson et al. (1987) has been developed from the abrasion-ablation model, but that does not show any considerable energy dependence. Garrard et al. (1995) have given a parametric fit for relativistic ultraheavy ($Z \geq 30$) projectiles in a wide target range from H to Pb, involving the parameters like projectile charge and mass number, kinetic energy of the projectile, target charge and mass numbers and charge change of the fragments. This formulation shows a very strong energy dependence especially for the H target.

So, there left the scope to analyse how the different available partia cross section data affects a Cosmic Ray propagation through ISM.

2 Cosmic Ray Propagation in the ISM:

In the present work we have taken an attempt to investigate the effect of partialcross sections on cosmic ray propagation. Our scheme is to consider a known source abundance and then to propagate them, using different partial cross sections.

To simulate the propagation of the cosmic ray nuclei through the Interstellar Medium (ISM), a simulation program initially developed by Hollabaugh (1988), has been adopted. This formulation is based on the Leaky Box Model of CR propagation. A diffusion equation can be written for this propagation which describes the flux of the species of particle at any time.

$$\frac{\partial N}{\partial t} = Q_i - D_i \frac{\partial^2 N_i}{\partial x^2} - nvs_i N_i + \sum_j \left(nvs_j N_j \right) \qquad (1)$$

N_i is the density of species i, D_i is a diffusion coefficient, Q_i is the source production of i, n is the ISM density, and v is the velocity of the particles, s_i, S_j are the total and partial interaction cross sections involved for a particular specimen i.

According to this equation, the rate of change of species i is equal to the source concentration minus the loss by diffusion, minus the loss by interaction or decay, plus the production by interaction or decay of i by species j.

As the particle diffuses through the galaxy, it may finally escape. The distance it has travelled before escape is the escape length x_{esc} in cm. Then the mean escape length λ_{esc} can be defined as

$$\lambda_{esc} = \rho . x_{esc} = \rho \beta c t_{esc} \qquad (2)$$

where ρ is the ISM density in g/cm^3 and t_{esc} is the cosmic particle life time in the galaxy before escape.

Now, this escape length is a function of particle energy. An exponential path length distribution is chosen here for the solution of the above diffusion equation. P is the exponential distribution of escape probability. If x is a small interval of x_{esc} then $P = \exp\left(-x/\lambda_{esc}\right)$ is the probability of particle escape in the interval x.

As a particle travels from one point to another it has a probability to interact with the ISM hydrogen. For this the total interaction length λ_{int} has been considered which can be defined as

$$\lambda_{\text{int}} = \frac{10^4}{6.02\sigma_t} \qquad (3)$$

where A is the atomic mass of the target nuclei and σ_{t} is the total interaction cross section in millibarn.

The total interaction cross section has been evaluated from the empirical relation of Binns et al. (1987).

The product nuclei formed from this interaction is again dependent upon the partial cross sections and determination of this partial cross section is one of the largest difficulties in realistic propagation studies of cosmic rays.However, here different available partial cross section data are used to explore how much the propagation is controlled by these partial cross sections.The simulation program has been modified for introducing the computed partial cross sections of Tsao et al. (1993), Wilson et al. (1987) and Garrard et al. (1995).Combining these ideas the previous diffusion equation can be written as,

$$J_i\left(\frac{1}{\lambda_{esc}}+\frac{1}{\lambda_{\text{int}}}+\frac{1}{\lambda_{i,dec}}\right)=Q_i+\sum_{i,j} J_i\left(\frac{1}{\lambda_{i,j,spall}}+\frac{1}{\lambda_{i,j,dec}}\right) \quad (4)$$

This equation forms the basis of this simulation program.

We have taken the source spectrum given by Anders & Ebihara (1982) as a standard source abundance in this program and propagated it in the energy range 4.1 to 11 GeV/n to compare them with the observed satellite data of Engelmann et al. (1990) at 5.6 GeV/n. However, this comparison has been done basically to standardise our simulation program. Finally, we have seen the effect of using different partial cross section set on the derived nuclear abundances at the top of the atmosphere.

The total interstellar matter traversed by the cosmic rays is taken as 9 g-cm^2 according to Silberberg & Tsao (1990).

The solar modulation is taken to be 0.49 GV. The partial cross section values for Tsao et al. (1993) is taken at energy 7.10 GeV/n, Wilson et al. (1987) is taken at energy 6.52 GeV/n and that of Garrard et al. (1995) is taken at at energy 5.04 GeV/n. The acceleration factor is taken to be 0 for the present estimation and the energy index is taken as 2.5 for Fe-Sub Fe region.

3 Results:

In table-1, a comparison of the simulated Sub-Fe/Fe ratio at the top of the atmosphere has been made with the observed HEAO-3-C2 data of Engelmann et al. (1990).

TABLE-1

The table shows our simulation results on (Sc-Cr)/Fe ratio at the top Of the atmosphere derived from AA source spectrum using pcs from Garrard etal.(1995) along with that measured by Engelmann et al.(1990):

Methodology	Authors	(Sc-Cr)/Fe ratio
Theoretical	Present simulation result	0.272 ± 0.004
Experimental	HEAO-3-c2(1990)	0.300 ± 0.009

Our derived (Sc-Cr)/Fe ratio at the top of the atmosphere using different sets of partial cross sections, are displayed in table-2.

TABLE-2

The table shows presently derived (Sc-Cr)/Fe ratio at the top of the atmosphere from AE spectrum with different sets of partial cross-section data:

Presently derived with pcs from	(Sc-Cr)/Fe
Tsao et al.(1993)	0.555 ± 0.006
Wilson et al.(1987)	0.637 ± 0.007
Garrard et al.(1995)	0.272 ± 0.004

4 Conclusion:

We have derived the (Sc-Cr)/Fe ratio at the top of the atmosphere from the solar abundances of Anders & Ebihara (1982) using different sets of pcs after Tsao et), Wilson al. (1993et al. (1987) and Garrard et al. (1995). The formulations of Tsao et al. and Wilson et al. give comparable results, but they differs considerably when compared to the result obtained using the pcs of Garrard et al. The reason behind this may be our extrapolated use of the formula by Garrard et al. in the lower Z region (Z=21-26), whereas the formulation is for ultraheavy projectiles.

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