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# K-capture cosmic-ray secondaries and reacceleration

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**Abstract.** We have investigated the effect of reacceleration on interstellar flux of K-capture secondaries $^{49}$V and $^{51}$Cr. Several isotopic ratios for these two isotopes are calculated using the galactic diffusion model with and without distributed reacceleration. It is found that the statistical accuracy of the ACE experiment on itself is high enough to see a signature of reacceleration. However, the uncertainties in nuclear production cross sections are probably too large to conclude that reacceleration process took place.

## 1 Introduction

The isotopes $^{37}Ar$, $^{44}$Ti, $^{49}$V, $^{51}$Cr and others are produced by nuclear interactions during cosmic ray propagation in the interstellar gas. They rapidly decay by electron capture at low energies when energetic ions can have an orbital electron. The probability to have a bound electron strongly depends on energy. As a consequence, the surviving fraction of K-capture isotopes and the abundance of their decay products are strong functions of energy and are sensitive to the possible change of particle energy in the interstellar medium. This has led to suggestion (Silberberg *et al.*, 1983; Silberberg & Tsao, 1990; Soutoul *et al.*, 1998) that the measurements of secondary K-capture isotopes in low-energy cosmic rays at E < 1 GeV/nucleon could test the reacceleration hypothesis. The new ACE data (Niebur *et al.*, 2000) on the isotopic composition of titanium, vanadium, and chromium have high statistical accuracy, show energy dependence of the content of radioactive electron capture isotopes, and can be used for the comprehensive investigation of interstellar propagation of low energy cosmic rays.

In this paper we study two K-capture processes $^{51}$Cr $\rightarrow^{51}$V and $^{49}$V$\rightarrow^{49}$Ti. We have calculated several isotopic ratios involving K-capture process using disk-halo diffusion model with and without reacceleration (Jones *et al.*, 2001). The ef-

fect of reacceleration is discussed in the context of uncertainties existing in measured isotopic ratios and used nuclear fragmentation cross sections.

## 2 Propagation Calculations

We have performed propagation calculations using the one-dimensional diffusion model with a thin disk of cosmic ray sources and matter, and with an extended matter-free halo $|z| \leq H$. Both models are described in detail in our paper (Jones *et al.*, 2001). The cosmic rays diffuse through the Galaxy with a momentum dependent spatial diffusion coefficient $D$ and freely escape from the system at the halo boundaries . It is assumed that diffusion results from the particle scattering on interstellar turbulence. In addition to the spatial diffusion, the energetic particles in the model with reacceleration experience stochastic acceleration which is described as diffusion on momentum with diffusion coefficient $D_{pp} \propto p^2 V_a^2/D$, where $p$ is the particle momentum and $V_a$ is the Alfven velocity. The reacceleration occurs in the region $|z| \leq h_a$. Following Seo & Ptuskin (1994), we take $h_a = H/3$.

The escape length $X_e$, g/cm2, determines the mean matter thickness traversed by energetic particles observed in the Galactic disk without effects of fragmentation, decay, and energy change taken into account. The escape length is expressed through the parameters of the diffusion model as $X_e = \mu\beta cH/(2D)$, where $\mu( \approx 2.4 \cdot 10^{-3}$g/cm2) is the surface gas density of the Galactic gas disk, $\beta c$ is the particle velocity. It was found (Jones *et al.*, 2001) that the following sets of parameters give the best fit to the data on cosmic ray secondary Boron and sub-Iron (Sc+Ti+V) elements in two models under consideration ($R$ is the particle magnetic rigidity): $X_e = 11.8\beta$ g/cm2 at $R < 4.9$ GV, $X_e 11.8\beta(R/4.9\text{GV})^{-0.54}$ g/cm2 at $R \geq 4.9$GV in the model without reacceleration; and $X_e = 9.4 \cdot R^{-0.3}$ g/cm2 at all $R$, $V_a = 40$ km/s in the model with reacceleration (the value of $V_a$ depends on the size of the reacceleration region as $V_a \propto h_a^{-1/2}$). It is worth noting that the spatial diffu-

sion coefficient in the reacceleration model has more "natural" scaling on rigidity ($D \propto \beta R^{0.3}$ that corresponds to the cosmic ray scattering on a Kolmogorov type spectrum of interstellar turbulence. Stochastic reacceleration essentially modifies the spectra of primaries and secondaries below 10 GeV/n and reproduces the observed peaks in secondary/primary ratios at about 1 GeV/n.

The nuclear cross sections used in our calculations include the new primary cross sections in hydrogen targets for C through Ni at 600 MeV/n as described in Webber *et al.* (1998a,b), as well as the hydrogen cross sections for essentially all of the secondary nuclei from Li through Mn also at 600 MeV/n reported in Webber *et al.* (1998c). The energy dependence of these isotopic cross sections is updated and extended as well using earlier charge changing cross sections measured between 300 and 1700 MeV/n (Webber *et al.*, 1990) and at 15 GeV/n (Webber *et al.*, 1994) and assuming that the isotopic fractions are generally independent on energy as confirmed by these earlier measurements and those of the Transport Collaboration (Chen et *et al.*, 1997). The atomic cross sections for attachment of a free electron are calculated as in Letaw *et al.* (1984).

## 3   Results, Discussion and Conclusion

The results of propagation calculations for two isotopic ratios $^{49}$Ti/$^{49}$V and $^{51}$Cr/$^{51}$V are displayed in Figure (1). The solid curve represents the model without reacceleration and the dotted line corresponds to the reacceleration model. The experimental points are from new high resolution and high statistics data from the Cosmic Ray Isotope Spectrometer on the ACE spacecraft (Niebur *et al.*, 2000) and from the Ulysses experiment (Connell & Simpson,, 1999). Cosmic ray isotopes $^{51}$Cr and $^{49}$V are produced by fragmentation of heavier cosmic ray nuclides and decay only by electron capture. The calculated isotopic ratio $^{51}$V/$^{51}$Cr in both models shows strong dependence on energy. In the low energy region 100-300 MeV/n the effect of K-capture process is strong and the isotopic ratio is twice larger than a ratio calculated without K-capture process. The $^{51}$V/$^{51}$Cr isotopic ratio calculated in the model with reacceleration fits measured experimental points better than the model without reacceleration.

$^{51}$V/$^{51}$Cr- this isotopic ratio (Figure (1)) calculated in the reacceleration model at the energy of 200 MeV/n and modulation level of 500 MV is larger by 17% than the ratio obtained in the model without reacceleration. This difference is slightly larger than 1 sigma uncertainty in the ACE measurement. In Figure (1) the results for $^{51}$V/$^{51}$Cr from the reacceleration model (dotted line) are in better agreement with measured isotopic ratios than the model without reacceleration (solid line).

($^{51}$Cr+$^{51}$V)/52Cr - in Figure (2) we present the isotopic ratio ($^{51}$Cr+$^{51}$V)/$^{52}$Cr which involves parent and daughter and is constant with energy and independent on K-capture process. The propagation calculations from both models are in good agreement with measured isotopic ratio from ACE
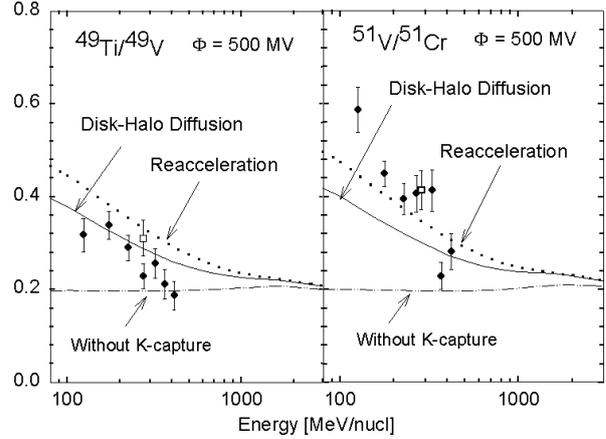


**Fig. 1.** $^{49}$Ti/$^{49}$V

experiment. This would indicate that used cross sections for fragmentation to $^{51}$Cr, $^{52}$Cr and $^{51}$V are rather well measured.
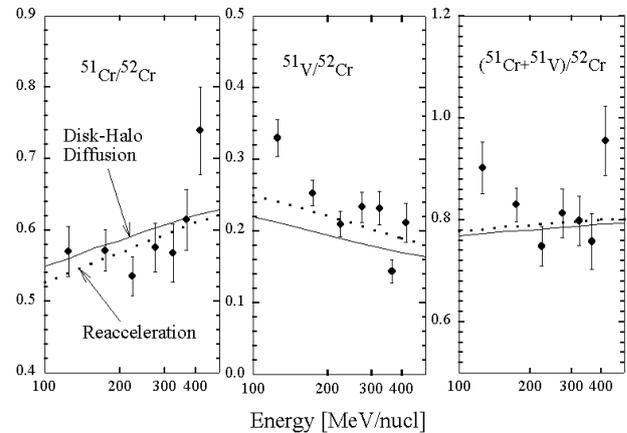


**Fig. 2.** Cr51 over Cr52

$^{51}$V/$^{52}$Cr - the results from propagation calculations (Figure (2)) indicate that the reacceleration model is in better agreement with measured ratios.

$^{51}$Cr/$^{52}$Cr  - for this isotopic ratio (Figure (2)) results from the reacceleration model agree with ACE experiment only slightly better than the model without reacceleration. The difference between both models for this isotopic ratio is smaller than one sigma uncertainty in ACE measurement.

$^{49}$Ti/$^{49}$V - this isotopic ratio calculated in both models is slightly higher than the measured ACE ratio. This could indicate that K-capture cross sections are too large or that fragmentation cross sections to $^{49}$Ti are too large or that to $^{49}$V are too small. The $^{49}$Ti isotope is almost completely secondary with negligible source abundance of $^{49}$Ti/56Fe = 0.02% . Most of fragmentation (80%) to $^{49}$Ti comes from

5 isotopes with the largest contribution from 56Fe ( 56Fe $\rightarrow$ $^{49}$Ti = 53.5%, 50V$\rightarrow$$^{49}$Ti = 8.7%, $^{52}$Cr$\rightarrow$$^{49}$Ti = 8.6%, $^{51}$Cr$\rightarrow$$^{49}$Ti = 5.2% and $^{50}$Ti $\rightarrow$ $^{49}$Ti = 3.9%).

The $^{49}$V is a pure secondary isotope with K-capture process. The 80% of fragmentation to $^{49}$V comes from 7 contributions ($^{56}$Fe$\rightarrow$$^{49}$V=50.8%, $^{50}$V$\rightarrow$$^{49}$V = 7.0%, $^{52}$Cr$\rightarrow$$^{49}$V = 4.6%, $^{51}$Cr$\rightarrow$$^{49}$V = 4.5%, $^{50}$Cr$\rightarrow$$^{49}$V = 4.3, $^{54}$Fe$\rightarrow$$^{49}$V = 4.6% and $^{57}$Fe$\rightarrow$$^{49}$V=4.3%).

($^{49}$V+$^{49}$Ti)/($^{46}$Ti+$^{47}$Ti+$^{48}$Ti) - This combined isotopic ratio Figure (3)) is used as a consitency test for propagation calculations. There is no K-capture effect in this ratio and it is almost constant with energy. The propagation calculations are higher than the average value from all 7 experimental points. This would indicate that fragmentation cross sections to $^{49}$Ti are too large. See also in the same figure $^{49}$Ti/($^{46}$Ti+$^{47}$Ti+$^{48}$Ti).
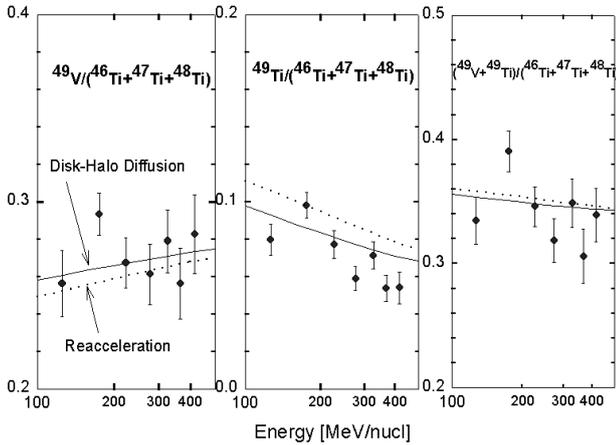


**Fig. 3.** V49 over Ti

$^{49}$**Ti**/($^{46}$**Ti**+$^{47}$**Ti**+$^{48}$**Ti**) - the propagation results (Figure (3) from both models are higher than the experimental points. This indicates that fragmentation cross sections to $^{49}$Ti are too large.

$^{49}$**V**/($^{46}$**Ti**+$^{47}$**Ti**+$^{48}$**Ti**) - both models are in agreement with experimental points. The difference between both models is small when compared to 1 sigma uncertainty in measured values.

Reduction in the production cross sections to $^{49}$Ti by 20% (twice more than is the uncertainty in the measured cross sections to $^{49}$Ti) would improve the agreement of both models with measured ($^{49}$V+$^{49}$Ti)(/$^{46}$Ti+$^{47}$Ti+$^{48}$Ti), $^{49}$Ti(/$^{46}$Ti+$^{47}$Ti+$^{48}$Ti) and $^{49}$Ti/$^{49}$V isotopic ratios. Such a reduction would give some advantage to the model with reacceleration. However, there are still uncertainties in the cross sections. For those isotopes near the centroid of the mass distributions for a given fragment charge, the accuracy is quite high, $\pm$3-5%. For isotopes away from the centroid, with lower sigma the accuracy deteriorates. So for example 56Fe to 52Cr should be good to $\pm$ 5%, 56Fe to 51Cr or 49V probably 5-10%, but 56Fe to 51V or 49Ti have much smaller

sigma and larger errors. The actual measured cross sections 56Fe to 51V and 49Ti are 6.3mb and 6.1mb respectively and we estimate the overall errors in these cross sections to be $\pm$ 10-15%. These errors are getting to be comparable to the difference between no acceleration and reacceleration which we estimate to be $\sim$17% at 200. The errors in the ACE data are probably at least $\pm$5%, so it is a very difficult problem to clearly see the effects of reacceleration.

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