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LETTER

Letter to the Editor

Evidence from Voyager and ISEE-3 spacecraft

Data for the decay of secondary K-electron capture isotopes during the propagation of cosmic rays in the Galaxy

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Abstract. New data from the cosmic ray experiment on the Voyager spacecraft confirms and extends earlier data from a similar experiment on the ISEE-3 spacecraft which indicates the possibility of the decay of certain K-capture isotopes during the interstellar propagation of galactic cosmic rays. These cosmic ray measurements, along with the cross section measurements, indicate that $\sim$25% of the K-capture isotopes ^{51}Cr and ^{49}V produced as secondaries have decayed at interstellar energy of $\sim$400 MeV/nuc. This suggests a possible interstellar energy gain $\sim$100 MeV/nuc out of the current interstellar energy $\sim$500 MeV/nuc. This measurement suggests that the study of the K-capture isotopes may now have reached a level that will soon provide definitive information on the amount of reacceleration that may occur during cosmic-ray propagation after an initial acceleration in the cosmic ray sources.

Key words: ISM: cosmic rays

1. Introduction

It has been recognized now for over 20 years that electron capture isotopes – whose decay depends on the attachment of a K-shell electron – produced as secondaries during the propagation of cosmic rays in the galaxy will decay during the lifetime of the cosmic rays arriving at the solar system. This attachment is strongly energy dependent and so provides information on the conditions of propagation and the interstellar energy at the time of attachment (Raisbeck & Yiou, 1971). A comparison of the measured abundance of these K-capture isotopes with detailed predictions of their expected abundance based on cross section measurements and propagation models may thus be used to determine how this attachment energy is related to the present energy for these nuclei – and so to provide information on whether the cosmic ray acceleration process actually occurs only over a short initial time or whether significant acceleration occurs throughout the lifetime of cosmic rays during which time the secondaries are produced. In addition, because the local interstellar energy can be estimated from the amount of decay of these isotopes, the amount of interplanetary energy loss can be estimated. This is important because most models of cosmic ray modulation in the heliosphere predict a "real" energy loss of a few hundred MeV/nuc during the course of this modulation (Gleeson & Axford, 1967; Goldstein, Fisk & Ramaty, 1970).

Several K capture isotopes can be studied to determine if this attachment and subsequent decay has occurred. Examples are: ^{57}Co $\rightarrow$ ^{57}Fe, ^{55}Fe $\rightarrow$ ^{55}Mn, ^{54}Mn $\rightarrow$ ^{54}Cr, ^{51}Cr $\rightarrow$ ^{51}V and ^{49}V $\rightarrow$ ^{49}Ti. The lifetimes of these isotopes against decay by K-capture is shorter than that for stripping of the attached K-electron even in the dense cold phase of the interstellar medium with densities $\simeq 10^2$-10^3 atoms/cm^3. Stripping is uneffective for preventing decay once attachment has occurred.

Previous attempts to observe this decay have been inconclusive for a number of reasons. Partly because the appropriate cross sections were not known accurately enough and partly because of the limitations of the cosmic ray data on the abundance of these isotopes. Now because of the addition of new Voyager data (Lukasiak et al., 1997a) to the already existing ISEE data base (Leske, 1993) on the isotopic composition of elements in the range Z=20–28, as well as improved cross section measurements of ^{56}Fe fragmentation (Webber, Kish and Schrier, 1990a) and improved predictive formulae for the unmeasured cross sections (Webber, Kish and Schrier, 1990b), it is now possible to examine this problem with a new level of precision. In this paper we concentrate on the Vanadium isotopes with comments as to why the other K-capture decay isotopes are more difficult to observe. For Vanadium, if electron capture decay has indeed occurred, there will be a maximum observable effect with respect to the isotopic composition predicted if no decay has occurred. This charge has 3 isotopes in cosmic rays; if decay occurs ^{51}V will be enhanced because of the decay of ^{51}Cr, ^{50}V will be unaffected and ^{49}V will be depleted as it decays into ^{49}Ti. The vanadium isotopes are mostly of secondary origin and the value of the predicted interstellar ^{51}V/^{49}V ratio at energies

Table 1. K-capture isotopes

	τ(n=0.3) 400 MeV/nuc	τ(n=0.3) 600 MeV/nuc	
49V	9.8 - 29 - 7.3	8.4 - 62 - 7.4	→ 49Ti
51Cr	9.5 - 24 - 6.8	8.2 - 53 - 7.1	→ 51V
54Mn	9.2 - 20 - 6.3	7.9 - 40 - 6.6	→ 54Cr
55Fe	9.0 - 17 - 5.9	7.8 - 36 - 6.4	→ 55Mn
57Co	8.8 - 15 - 5.5	7.6 - 31 - 6.1	→ 57Fe

The first number for each energy is the nuclear interaction lifetime in 10^6 yrs, the second number is the attachment lifetime and the third number is the combined lifetime.

below 1 Gev/nuc is weakly affected by the uncertainties of the abundances at the cosmic ray source.

2. Calculation of the characteristic decay times of K-capture isotopes

In the process of electron attachment an electron in the target medium becomes bound to the cosmic ray (Letaw, Silberberg and Tsao, 1984, see also Silberberg et al., 1991). This process is termed radiative attachment if the electron may be considered free and if a photon is emitted to conserve energy and momentum. The cross section for attachment of a free electron is calculated as that for the inverse process of the photoelectric effect using the principle of detailed balancing (Heitler, 1966; Meaker Davisson & Evans, 1952: Raisbeck & Yiou, 1971). The value of this cross section and of its energy dependence around 500 MeV/nuc agree within 10% or less with those taken from the curves of Letaw et al. (Letaw et al. 1985) and with the calculation of Crawford on argon at 400 Mev/nuc (Crawford, 1979). Radiative attachment dominates at cosmic ray energies above $\sim$200 MeV/nuc in an interstellar medium of normal cosmic abundances (Raisbeck & Yiou, 1971). For the isotopes listed in Table 1 stripping is neglected and the effective K-capture decay is determined by the attachment rate. The lifetimes are calculated for an IS medium with 90% H + 10% He and with a density n = 0.3 atoms cm^{-3}. In Table 1, we show the calculated lifetimes for nuclear destruction, radiative attachment (and subsequent K-capture) and their combination as a function of charge and at two interstellar energies. Note that the ratio of these lifetimes does not depend on the adopted value of the density of the medium.

3. The data and its interpretation

In Fig. 1 we show the predictions for the relative abundances of the V isotopes to be expected based on the standard Leaky Box propagation model (Lukasiak et al., 1994, 1997a), along with the combined measurements of the V isotopic composition from the Voyager (Lukasiak et al., 1997a) and ISEE spacecraft (Leske, 1993). This model assumes no decay of the K-capture isotopes. The ionisation losses in the interstellar medium are included in the calculation. The value of the characteristic time for escape from the confinement volume is tuned to fit accurately

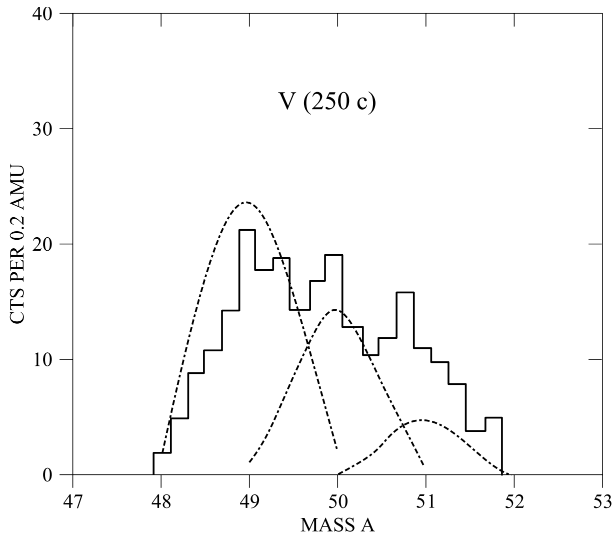

Fig. 1. Combined data from VOYAGER position of V nuclei. (Both experiments have essentially the same mass resolution therefore the data can be simply added). Prediction of the number of events from a Leaky Box propagation model assuming the same mass resolution, is shown ^{51}Cr decay, and the deficiency of ^{49}V, $\sim$25% of which has decayed to ^{49}Ti, are clearly seen.

the B/C ratio below 1 GeV/nuc. Using this ratio as a reference gives the other calculated secondary to primary ratios for nuclei with mass number 10 to 15 to the same accuracy as the B/C ratio can be measured (Webber & Soutoul 1989). The values of isotopic abundance ratios of mainly secondary isotopes in the iron group are very weakly dependent on the value of this characteristic time for escape taken within reasonable limits: a change of the characteristic time for escape (a free parameter of the calculation) resulting in a change of $\simeq$20% of the calculated B/C ratio results in a corresponding change of about 2% of the ^{51}V /^{49}V ratio. This and other isotopic ratios do depend on the cross sections – mainly from ^{56}Fe which have been measured to an accuracy of a few percent (Webber, Kish and Schrier, 1990a) and the secondary production as a function of energy from Mn and Cr which can be calculated from the parametric formula (Webber, Kish and Schrier, 1990b). The ratios of the V isotopes are of course, very sensitive to the K-capture decay of ^{51}Cr and ^{49}V but not on the density of the medium where attachment and other catastrophic losses are taking place. The Voyager and ISEE measurements in combination and individually (see original references) clearly show both an enhancement of ^{51}V and a depletion of ^{49}V relative to the predictions, as is expected if some decay has occurred. In Fig. 2 we show the predicted and observed isotopic fractions of V. In Fig. 3 we show the ^{51}V/^{49}V ratio as a function of energy – in effect the combined effects of ^{49}V depletion and ^{51}V enhancement. We note that the predicted ratio of these isotopes assuming no K-capture decay is almost constant with both energy and modulation level at a value of 0.21. (The solar modulation levels are ϕ = 480 MV for Voyager and ϕ = 700 MV for ISEE-3). The ratio of ^{51}V/^{49}V measured by Voyager is somewhat larger than that of ISEE-3 but both of the observed ratios are much larger than the predicted value of

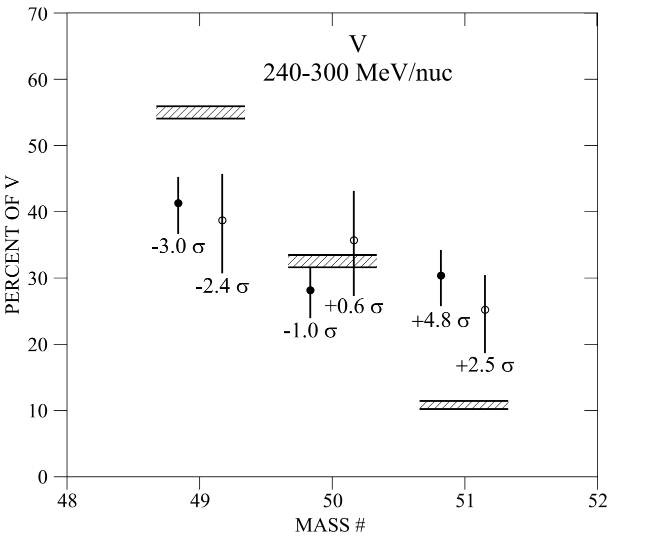

Fig. 2. The isotopic fractions of V, open circles: ISEE-3 (Leske, 1993), full circles: VOYAGER (Lukasiak et al., 1997a), hatched horizontal bars: values calculated witout decay.

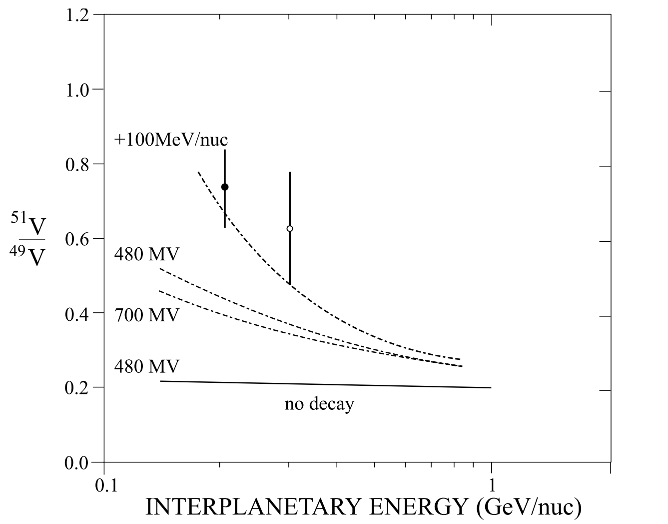

Fig. 3. The ^{51}V/^{49}V ratio as a function of the interplanetary kunetic energy. Open circles: ISEE-3 (Leske, 1993), full circles: VOYAGER (Lukasiak et al., 1997a), full curve: the ratio calculated with no decay, dashed dotted curves: the ratio calculated with decay. The solar modulation parameter value is either 480 MV or 700 MV as indicated. The upper dashed dotted curve is with 480 MV, attachment and decay taking place at an interstellar energy value 100 Mev/nuc below that of the observation.

0.21. We believe this provides convincing evidence that this decay has indeed occurred in interstellar space. This conclusion is not affected by the uncertainties or the abundances at the cosmic rays source. The abundances of isobars 49(Ti) and 51(V) at the cosmic ray source, taken solar (and decayed) are a small fration ($<$ 3%) of the spallogenic yield.

The question of what this evidence for decay means in terms of possible interstellar re-acceleration and/or interplanetary energy loss is somewhat more difficult to answer, however. The base ^{51}V/^{49}V ratio in Fig. 3 is calculated using the standard numerical diffusion-convection model for interplanetary modulation (Goldstein, Fisk and Ramaty, 1970), in which the effective average interplanetary energy loss is $\sim$240 MeV/nuc for the Voyager measurement and 350 MeV/nuc for the ISEE measurement as a result of the different modulation levels. No attachment is assumed. We now calculate the expected ratios assuming that radiative attachment occurs and that the attachment energy is the same as the current interstellar energy. The average measurements energy are 210 and 300 MeV/nuc for the Voyager and ISEE-3 instruments. The predicted ratios are now larger (but still smaller than the data) since some decay ($\sim$ 10–20%) is expected to occur even at the current interstellar energies for Voyager and ISEE. These predictions, shown as the dashed curves in Fig. 3, are now split because of the different interstellar energies of the two measurements. To match more closely the observed and predicted ratios we must assume that either; 1) There has been some energy gain between attachment and the current energy of these isotopes in interstellar space or 2) interplanetary energy loss is less than that assumed in the standard modulation models. The dotted curve in Fig. 3 shows the prediction if attachment takes place at an interstellar energy $\sim$100 MeV/nuc below that of the observations. This curve represents the observations quite well.

Only radiative attachment has been considered here. Non-radiative attachment (the so called Brinkman-Kramers cross section on heavy ions) has not been calculated theoretically. Measurements suggest that this cross section is $<$1% of the radiative one down to $\sim$300 MeV/nuc (interstellar energy) in a medium with interstellar composition (Raisbeck et al. 1978, Crawford 1979).

4. Other K-capture isotopes

From Table 1 it is clear that in addition to ^{49}V and ^{51}Cr there are several other K-capture isotopes that might be expected to decay. If, in fact, $\sim$25% of ^{49}V has decayed then from Table 1 it is seen that $\sim$38% of ^{57}Co should also decay. The Voyager results on the ^{57}Co abundance (Lukasiak et al., 1997b) are indeed lower than the prediction from secondary production only with no decay – but the data errors are large, the results being based on only 7 ^{57}Co events. This decay will contribute only a small increase to the much larger ^{57}Fe source abundance (although we note that Connell & Simpson, 1997, find a larger than expected source abundance of ^{57}Fe).

Connell & Simpson, 1997 find a finite source abundance of ^{55}Fe. For ^{55}Mn (the decay product of ^{55}Fe) the Voyager results (Lukasiak et al., 1997a) are 0.8 σ ($\sim$11%) greater than the prediction for interstellar production plus a 1.1%$\times^{55}$Fe source abundance. Evidence for ^{55}Fe decay is thus less convincing than for ^{49}V and ^{51}Cr and depends on the assumed ^{55}Mn source abundance.

The observation of the possible K-capture decay of ^{54}Mn into ^{54}Cr is complicated by the fact that overall roughly $\sim$70% of ^{54}Mn appears to have decayed (Duvernois, 1997; Lukasiak et al., 1997a) and this decay is attributed to β-decay into ^{54}Fe with an estimated half-life $\sim 1.2\times10^6$ yr. (This β-decay lifetime has not yet been measured in the laboratory). If some of the observed ^{54}Mn decay is, in fact, due to K-capture decay then this portion of the decay would appear as an enhanced ^{54}Cr abundance. The Voyager abundance of ^{54}Cr is indeed measured to be 1.6 σ (+90%) above the propagation calculations. The excess ^{54}Cr/^{56}Fe fraction of 0.45% implied by the Voyager data would be consistent with a K-capture contribution $\sim$20% to the decay of ^{54}Mn along with a correspondingly longer β-decay lifetime $\sim 1.8\times10^6$ yr.

So overall the data on the other K-capture isotopes is suggestive of decay although not at the same statistical level as for ^{49}V and ^{51}Cr. In particular, none of the other measurements are inconsistent with the observations reported here for ^{49}V and ^{51}Cr.

5. Summary and conclusions

We have presented evidence from the Voyager and ISEE spacecraft data that the decay of certain K-capture isotopes has occurred in interstellar space. This is obtained from a study of the relative abundances of cosmic ray Vanadium isotopes, ^{49}V decaying into ^{49}Ti and ^{51}Cr decaying to V^{51}. These measurements show that $\sim$25% of these isotopes have decayed. The interpretation of this decay in terms of interstellar energy changes during propagation is not completely straight-forward but if it is assumed that interplanetary energy loss is correctly described in the current models for solar modulation, then this data would imply an interstellar energy difference between attachment of the K-electron during propagation and the present time of up to $\sim$100 MeV/nuc. This value is in the nature of an upper limit. To expand this study further this decay needs to be confirmed for the other K-capture isotopes and needs to be carried out at different solar modulation levels and different energies – but this technique holds considerable promise for providing answers to two fundamental questions in the study of cosmic rays. 1) How much post-acceleration or re-acceleration actually occurs after the initial cosmic ray acceleration in astrophysical sources? and 2) Does the interplanetary energy loss predicted in the present solar modulation theories actually occur, thus transforming the interstellar spectrum?

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