Electron-capture Isotopes Could Constrain Cosmic-Ray Propagation Models

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Abstract

Electron capture (EC) isotopes are known to provide constraints on the low-energy behavior of cosmic rays (CRs), such as reacceleration. Here, we study the EC isotopes within the framework of the dynamic spiral-arms CR propagation model in which most of the CR sources reside in the galactic spiral arms. The model was previously used to explain the B/C and sub-Fe/Fe ratios. We show that the known inconsistency between the $^{49}$Ti/$^{50}$V and $^{51}$V/$^{53}$Cr ratios remains also in the spiral-arms model. On the other hand, unlike the general wisdom that says the isotope ratios depend primarily on reacceleration, we find here that the ratio also depends on the halo size ($Z_h$) and, in spiral-arms models, also on the time since the last spiral-arm passage ($\tau_{\text{arm}}$). Namely, EC isotopes can, in principle, provide interesting constraints on the diffusion geometry. However, with the present uncertainties in the lab measurements of both the electron attachment rate and the fragmentation cross sections, no meaningful constraint can be placed.

Key words: cosmic rays – diffusion – Galaxy: kinematics and dynamics

1. Introduction

Observations of cosmic-ray (CR) composition can provide insight about the origin of CRs, their initial composition, their path length distribution (PLD), and the interaction they undergo as they propagate in the interstellar medium. Such observations include the ratio between secondary to primary cosmic rays, including the boron to carbon (B/C) ratio, the sub-iron (scandium through manganese) to iron (sub-Fe/Fe) ratio, the positron fraction ($e^+/(e^- + e^+)$), and the ratios between the EC’s daughter and parent isotopes we study here. The latter are known to constrain the process of reacceleration, but as we show below, they can also be used, at least in principle, to constrain diffusion models.

If one calculates the secondary to primary ratio under the simplest leaky-box model or a “disk-like” model (with an azimuthally symmetric CRs source distribution), one finds that the ratio drops with energy (Cesarsky 1980). Indeed, the positron fraction below 10 GeV and the nuclei ratios above 1 GeV/nuc. exhibit this behavior. However, the positron fraction above 10 GeV and nuclei spectra below 1 GeV/nuc. appear to be behave differently (Strong & Moskalenko 1998; Adriani et al. 2009; Oliva et al. 2013). A disk-like model must include Galactic winds, reacceleration, or ad hoc assumptions on the diffusivity to explain the observed behavior of the nuclei ratios (Strong et al. 2007; di Bernardo et al. 2010), while the behavior of the positrons require either astrophysics solutions such as pulsars (e.g., Harding & Ramaty 1987; Aharonian et al. 1995; Chi et al. 1996; Profumo 2012; Hooper et al. 2009), or more exotic physics such as dark-matter decay (e.g., Bergström et al. 2008; Ibarra & Tran 2008).

Unlike a disk-like model, a spiral-arms model, in which a significant fraction of CR sources are located at the galactic spiral arms—a place where star formation is enhanced, hence young supernova remnants (SNRs) are abundant—can explain these anomalies at the outset. Shaviv et al. (2009) showed that by considering the CR sources to be at a finite distance from Earth, as expected from the spiral structure, one recovers the positron fraction spectrum. Moreover, Benyamin et al. (2014) recovered the B/C ratio also at low energies by taking the spiral arms to be dynamic. The astrophysical motivation of the spiral-arms model and its success in explaining these phenomena has motivated us to explore other predictions of this model.

Another interesting problem arises when the grammage required to explain the B/C ratio is compared with the sub-Fe/Fe ratio. When doing so, it reveals that the latter ratio requires about 20% more grammage than the former ratio in a disk-like model (Garcia-Munoz et al. 1987; Davis et al. 2000). Garcia-Munoz et al. (1987) proposed a solution to this problem by cutting the short path lengths from the CR PLD. Obviously, taking the source to be primarily in the spiral arms naturally causes a paucity in short path lengths. In a later study, the Ulysses-HET group (DuVernois et al. 1996) also tested the option of truncating the short path lengths and found that the this is not necessary. Namely, a simple exponential power law (as is the case in disk-like and leaky-box models) is sufficient to recover their own observations. However, the Ulysses-HET sub-iron/iron measurement is clearly well below other measurement (while the B/C is consistently the same), which explains why a simple pulsed laser deposition (PLD) is enough when only their measurement is considered. In Benyamin et al. (2016), we have shown that a spiral-arms model resolves this anomaly by finding the optimal model parameters required to separately recover the B/C and sub-iron/iron. It was shown that while the disk-like model does not recover the two ratios with consistently the same model parameters, the spiral-arm model does.

Here, we continue our investigation of the iron group CR nuclei (scandium through nickel)\(^\dagger\) within the context of the spiral-arm model, and focus on isotopes that decay through electron capture (EC). At low energies, electrons are bound to the nuclei and, as a consequence, these isotopes rapidly decay through EC. However, at higher energies, typically above 1 GeV/nuc., these isotopes are stripped of their electrons and this inhibits their decay. The probability for having bound

\(^\dagger\) The iron group includes the isotopes of scandium through nickel, with iron and nickel being the primaries and the rest secondaries. The sub-iron group is a sub group of the iron group that includes scandium through manganese.
electrons depends on two processes: the stripping and the attachment of electrons. Both are strongly dependent on energy (Letaw et al. 1985). However, because the EC decay timescale is generally much shorter than the stripping timescale, the isotope ratios basically depend on the attachment rate.

Niebur et al. (2000) reported the first measurements of $^{44}$Ti, $^{49}$V, $^{51}$Cr, $^{55}$Fe, and $^{57}$Co from the Cosmic Ray Isotope Spectrometer (CRIS) on board the Advanced Composition Explorer (ACE). In particular, they measured the $^{49}$Ti/$^{49}$V and $^{51}$V/$^{51}$Cr ratios. Evident from the observations is a very strong dependence on energy: the ratios decrease with energy. As the enumerator in these ratios is the stable daughter product of the EC of the parent isotope in the denominator, the ratios reflect the EC reaction rate and therefore the probability for the parent isotope to be stripped.

Jones et al. (2001) modeled the isotopic ratios using the weighted-slab model, while assuming different assumptions on the retention of electrons and reacceleration. They showed that complete stripping results in almost energy-independent ratios and therefore cannot explain the decrease with energy. In other words, there must be a transition from unstripped to stripped isotopes. The decrease with energy of the two ratios $^{49}$Ti/$^{49}$V and $^{51}$V/$^{51}$Cr is consistent with this interpretation as well.

Jones et al. (2001) then tried to explain the measurements by assuming that the nuclei retain their bound electrons at low energies and then reaccelerate to higher energies on their way to the solar system. The time spent at low energies will cause the EC isotopes to produce more daughter isotopes compared with CRs that did not spend time at low energies.

In a subsequent study, Niebur et al. (2001) showed that the cross section to bind electrons from the interstellar medium (ISM) to stripped nuclei is increasing for progressively smaller energies. For energies lower than a few hundred MeV/nuc., the timescale is shorter than the escape (and therefore typical age) of the cosmic rays. However, even at a few MeV/nuc., the attachment rate timescale is still much longer than the EC decay. This means that at energies of up to a few 100 MeV/nuc., the attachment process is dominant in determining the EC isotope ratios. They also considered reacceleration as do Jones et al. (2001), but due to the large electron attachment cross section that they include, Niebur et al. (2001) require a more feasible higher initial energy from which to accelerate these isotopes than do Jones et al. (2001).

However, both Jones et al. (2001) and Niebur et al. (2001) obtained inconclusive results; some of the observations were more consistent with models that include reacceleration (in particular, the $^{51}$V/$^{51}$Cr isotopes ratios), while other observations indicate the opposite (the $^{49}$Ti/$^{49}$V isotopes ratio). Both Jones et al. (2001) and Niebur et al. (2001) point out that the main problem in reaching any firm conclusions was the uncertainty in the fragmentation cross sections. Namely, the above inconsistency cannot be resolved with just reacceleration.

This conclusion about the fragmentation cross sections was reaffirmed by Niebur et al. (2003), who showed that the typical 10%–20% uncertainty in the fragmentation cross sections (Webber et al. 2003) can explain away the discrepancy between the above two isotope data sets. For example, reducing the $^{49}$Ti fragmentation cross section by 15% will resolve the discrepancy. We elaborate on this correction in Section 5.

We note that the CRIS/ACE results are not the first to have reached these conclusions. They are consistent with the previous measurements by the Ulysses HET team (Connell 1999) of a single data point at 300 MeV/nuc. (but with a similar error bar). These authors also concluded that some isotopes are consistent with reacceleration while others are consistent with no acceleration.

All of these studies were done within the standard disk model. One could have hoped that like other inconsistencies, this one will be resolved when we consider a dynamical spiral-arms model instead. Here, we show that the inconsistency between atomic mass 49 and 51 isotopes also remains in this model. This points to the same conclusion that there might be a problem with the fragmentation cross sections. We also show that while the power-law index of the cross sections’ energy dependence required to fit the observations agree with the lab experiments (Wilson 1978; Crawford 1979); the attachment normalization needed to fit the data varies depending on the halo size, $\delta_h$, and the time since last spiral-arm passage, $\tau_{\text{arm}}$.

Section 2 begins by briefly describing the spiral-arms model and the nominal model parameters. We review the data used in Section 3. In Section 4 we carry out an extensive analysis of the model, including a parameter study used to find a fitting formula for the attachment rate that recovers the $^{49}$Ti/$^{49}$V and $^{51}$V/$^{51}$Cr ratios. The implications of these results are discussed in Section 5.

2. The Model

SNRs are generally believed to be the sources of the Galactic CRs. The spiral-arms model assumes that, as SNRs are more abundant in galactic spiral arms, these arms are the main source of CRs. At low energies, the CRs diffuse slowly and the dynamical motion of the spiral arms cannot be neglected. Benyamin et al. (2014) describes a fully 3D numerical code for CRs diffusion in the Milky Way under these assumptions. The code enables us to explore dynamic spiral arms as the main source of the CR. Using this model, Benyamin et al. (2014) recovered the B/C ratio and demonstrated that the dynamics of the spiral arms has a notable effect on the ratio between secondary and primary CRs, which below 1 GeV/nuc. increase with the energy.

Benyamin et al. (2016) showed that a spiral-arms model, unlike a disk-like model, can explain the discrepancy between the grammage implied by the B/C ratio and by the sub-Fe/Fe ratio. Naturally, the spiral-arms model requires different diffusion parameters than those commonly used in the Galactic disk model. The optimal parameters required to fit the B/C, sub-iron/iron and $^{10}$Be/$^{9}$Be ratios within the dynamic arms and homogeneous disk models are summarized in Table 1 (Benyamin et al. 2016, 2014).

Our code is different from present-day simulations (such as GALPROP, Strong & Moskalenko 1998, and DRAGON, di Bernardo et al. 2010) that solve the partial differential equations (PDE) describing diffusion in that we use a Monte Carlo methodology. This allows for more flexibility in adding various physical aspects to the code (such as the spiral-arm advection), though at the price of reduced speed. Here, we will only discuss the changes we recently made to explore the EC reactions. The full details of the code and of the the model are found in Benyamin et al. (2014, 2016).
Table 1: Nominal Model Parameters

| Parameter | Definition | Value for Spiral-arm Model | Value for Disk-like Model |
|-----------|------------|-----------------------------|---------------------------|
| $Z_h$     | Half halo height | 250 pc | 1 kpc |
| $D_0$     | Diffusion coefficient normalization | $1.2 \times 10^{27}$ | $5 \times 10^{27}$ |
| $\delta$  | Spectral index | 0.4 | 0.5 |
| $t_{\text{last}}$ | Last spiral-arm passage | 5 Myr | ... |
| $i_4$     | 4-arms set’s pitch angle | 28° | ... |
| $i_2$     | 2-arms set’s pitch angle | 11° | ... |
| $\Omega_4$ | Angular velocity of the 4-arms set | (15 km s$^{-1}$) | ... |
| $\Omega_2$ | Angular velocity of the 2-arms set | (25 km s$^{-1}$) | ... |
| $f_{SN,4}$ | Percentage of SN in the 4-arms set | 48.4% | ... |
| $f_{SN,2}$ | Percentage of SN in the 2-arms set | 24.2% | ... |
| $f_{SN,CC}$ | Percentage of core collapse SN in the disk | 8.1% | 80.7% |
| $f_{SN,1a}$ | Percentage of SN Type Ia | 19.3% | 19.3% |

Notes.

a We assume a power-law dependent diffusion, $D = D_0 \beta (R/3 \text{ GV})^2$, where $R$ is the rigidity and $\beta$ is $v/c$. However, throughout the paper, the term “diffusion coefficient” actually refers to the normalization $D_0$ and not $D(R)$. $\beta$ Note that the disk-like model diffusion coefficient is at the lower end of values found in the literature. This is because the model has a relatively small halo (1 kpc), but also because we require the model to recover the sub-iron/iron ratio and not the B/C ratio typically fitted in the literature.

2.1. Attachment Rate Formula

Letaw et al. (1985) studied the EC reaction in CRs using experimental data collected by Wilson (1978) and Crawford (1979). In Figures 1 and 2 of Letaw et al. (1985), one can see that for $21 < Z < 28$ and for energies of a few 100 MeV/nuc. the mean free path for attachment of an electron is roughly $\lambda_{\text{attachment}} \approx 1 \text{ g cm}^{-2}$, while for the stripping of an electron it is roughly $\lambda_{\text{stripping}} \approx 10^{-3} \text{ g cm}^{-2}$, which correspond to timescales of $\tau_{\text{attachment}} \approx 5 \text{ Myr}$ and $\tau_{\text{stripping}} \approx 5 \times 10^{-3} \text{ Myr}$, respectively. For the isotopes $^{44}\text{Ti}$, $^{49}\text{V}$, $^{51}\text{Cr}$, $^{55}\text{Fe}$, and $^{57}\text{Co}$ the decay timescale is between several days to a few years, much smaller than $\tau_{\text{stripping}}$, implying that we can neglect the stripping process for those isotopes and assume that they decay immediately after they attach an electron from the ISM. However, for $^{53}\text{Mn}$ and $^{59}\text{Ni}$, the half-life time for the EC decay is 3.7 Myr and 0.076 Myr, respectively, which is much longer than $\tau_{\text{stripping}}$. This allows one to neglect the decay process and assume that these isotopes will be stripped off their electrons before they could decay and therefore remain stable.

When interpolating the data of Letaw et al. (1985) fit for the electron attachment mean free path, one can see that the energy dependence of the attachment cross section is a power law of the form

$$\sigma_\text{a}(E, Z) = N Z^\nu (E/500 \text{ MeV})^\mu,$$

3. Observational Data Sets

We compare the model predictions for the $^{49}\text{Ti}/^{49}\text{V}$ and $^{51}\text{V}/^{51}\text{Cr}$ ratios with the two CRIS data sets (Niebur et al. 2003), one collected during the solar minimum years, 1997–1999, and one for the solar maximum years, 2000–2003, with average solar modulation of 510 MV and 920 MV, respectively (Usoskin et al. 2011). For each observation, there are 14 data points between 100 MeV/nucleon and 1 GeV/nucleon. To account for the solar wind modulation, the energy of each specie outside the solar system obtained in the simulation is mapped to the modulated energy inside the solar system through $E_{\text{obs}} = E - (Z/A) \times \phi$, where $\phi$ is the modulation potential. The modeled species ratios can then be calculated and compared with the observations at a given observed energy from which a $\chi^2$ can be calculated.

The data (and the model fits) are depicted in Figure 1.

4. Results

4.1. A Disk-like Model

We begin with the analysis of the disk-like model. We consider a nominal halo size of $Z_h = 1$ kpc and a diffusion coefficient normalization of $D_0 = 5 \times 10^{27} \text{ cm}^2 \text{s}^{-1}$ that recovers the observed sub-Fe/Fe ratio, and its comparison with Letaw et al. (1985). The rationale of using the values that fit the sub-Fe/Fe ratio and not the B/C ratio is because the EC isotopes are much closer to iron and the other isotopes that we consider here. Figure 2 provides a contour plot of the $\chi^2$ fit between model and observations for the two parameters in the attachment process formula, $N$ and $\mu$.

Figure 2 depicts the $\chi^2$ fit to the data sets, when separately fitting the $^{51}\text{V}/^{51}\text{Cr}$ data, the $^{49}\text{Ti}/^{49}\text{V}$, and fitting them together. One can easily see that there is an inconsistency. While the observations for $^{51}\text{V}/^{51}\text{Cr}$ require a high normalization factor and a low power-law index, the observations for $^{49}\text{Ti}/^{49}\text{V}$ require a lower normalization factor and a higher power-law index. This inconsistency between the two observations was already demonstrated in previous works (Jones et al. 2001; Niebur et al. 2001, 2003; Webber et al. 2003).

Despite this inconsistency, the optimal power-law index for the combined $\chi^2$ for both data sets, $\mu = 2.1 \pm 0.7$, is in agreement with the results of Letaw et al. (1985), $\mu = 1.8 \pm 0.1$. Even for each separate set of isotope ratio measurements, $\mu = 1.8$ is inside the respective 2σ region. We

\[ \frac{49}{51} \text{Ti}/\text{V} = 0.2 \pm 0.1 \text{ for } 20 < Z < 28. \]
note, however, that the significance contours denote only the statistical uncertainties, but not the unknown systematic errors that should exist given the uncertainty concerning the cross section.

In addition to the fact that the normalization cross section required to explain that the two observations are inconsistent with each other, they are also inconsistent with Letaw et al. (1985) who require a somewhat larger attachment cross section.

For the disk-like model, the $^{49}$Ti/$^{49}$V data require a normalization factor of $N = 5.6 \pm 0.8 \times 10^{-5}$ mb, the $^{51}$V/$^{51}$Cr data require $N = 8.2 \pm 0.7 \times 10^{-5}$ mb, while Letaw et al. (1985) finds $N = (1.2 \pm 0.2) \times 10^{-4}$ mb, which is about a factor of 1.5 higher than our result.

Next, we proceed to check whether the inconsistency between the two sets of observations and the inconsistency in the normalization of the cross section between our results and those of Letaw et al. (1985) are an outcome of the model parameters or whether these inconsistencies remain for all disk-like models.

Figure 3. Contour plot of $\chi^2$ for a disk-like model with a halo size of $z_h = 3$ kpc and a diffusion coefficient of $D_h = 1.5 \times 10^{25}$ cm$^2$ s$^{-1}$. Similar to Figure 2, the red contours correspond to the $^{51}$V/$^{51}$Cr fit, the blue contours correspond to the $^{49}$Ti/$^{49}$V fit, and the dashed purple lines correspond to the combined $\chi^2$ calculation. Note that the discrepancy between the two observations remains the same as in Figure 2.

Figure 2. Contour plot of $\chi^2$ fit for a disk-like model with halo size of $z_h = 1$ kpc and diffusion coefficient of $D_h = 4 \times 10^{22}$ cm$^2$ s$^{-1}$. The red contours correspond to the $^{51}$V/$^{51}$Cr fit, the blue contours correspond to the $^{49}$Ti/$^{49}$V fit, and the dashed purple lines correspond to the combined $\chi^2$ calculation. Note the discrepancy between the $^{51}$V/$^{51}$Cr and the $^{49}$Ti/$^{49}$V fits: while the observation for $^{51}$V/$^{51}$Cr requires high normalization and a low power-law index, the observation for $^{49}$Ti/$^{49}$V requires a smaller normalization and a higher power-law index. The green point denotes the electron attachment cross section derived by Letaw et al. (1985), based on the lab measurements of Crawford (1979) and Wilson (1978), which is required to explain experimental data.

The data require $N = (8.2 \pm 0.7) \times 10^{-5}$ mb, while Letaw et al. (1985) finds $N = (1.2 \pm 0.2) \times 10^{-4}$ mb, which is about a factor of 1.5 higher than our result.

Next, we proceed to check whether the inconsistency between the two sets of observations and the inconsistency in the normalization of the cross-section between our results and those of Letaw et al. (1985) are an outcome of the model parameters or whether these inconsistencies remain for all disk-like models. Figure 3 depicts the $\chi^2$ fit for a disk-like model with a halo size of $z_h = 3$ kpc and diffusion coefficient of $D_h = 1.5 \times 10^{25}$ cm$^2$ s$^{-1}$.

Evidently, the discrepancy between the two sets of observations remains for different halo sizes; however, a large
section’s normalization factor is determined from the two EC data sets.

4.2. The Normalization Dependence on $z_h$ in a Disk-like Model

When varying the Galactic halo size, one has to take into account other observational constraints on the secondary to primary ratios, such as $B/C$ or sub-iron/iron. In fact, imposing the sub-iron to iron ratio measurements imposes the linear relation $D_0/z_h = (5 \pm 1) \times 10^{-27} \text{ (cm}^2 \text{s}^{-1}) \text{ kpc}^{-1}$. Namely, for each $z_h$, there is a corresponding diffusion coefficient normalization, $D_0$.

We note again that under the disk-like models, the $B/C$ ratio requires a different normalization for the diffusion coefficient than the sub-iron/iron ratio (Garcia-Munoz et al. 1987; Davis et al. 2000; Benyamin et al. 2016). We choose here the diffusion normalization factor corresponding to the sub-iron/iron data because the EC isotopes belong to the iron group as well.

Next, we now fix the attachment cross sections power-law index, $\mu = 1.8$. This value is consistent with the results of Letaw et al. (1985) and with ours. With these constraints on $\mu$ and $D_0$, we can now proceed to obtain the fitted attachment cross-section normalization, $N_{\text{disk}}$, as a function of $z_h$:

$$N_{\text{disk}} = (8.0 \pm 0.7) \times 10^{-5} \times (z_h/1 \text{ kpc})^{0.27 \pm 0.04} \text{ mb.} \quad (2)$$

One can easily see that in a disk-like model a halo size of about $z_h \approx 3$ to 5 kpc is required to match the results of Letaw et al. (1985).

4.3. A Spiral-arms Model

We now proceed to study our nominal spiral-arm model from Benyamin et al. (2016). In particular, we are interested in finding the optimal parameters (of the attachment process formula) that recover the observations. Figure 4 depicts a contour map of $\chi^2$ similar to Figures 2 and 3, but for the spiral-arms model.

As is the case in the disk-like model, the optimal power-law index for the combined $\chi^2$ calculation in the spiral-arms model is $\mu = 1.9 \pm 0.4$. This value also agrees with the results of Letaw et al. (1985). Nevertheless, the inconsistency between the required cross-section normalization of the two observations remains the same as in the disk-like model and all other previous works. This suggests that by the changing the...
diffusion parameters or geometry one cannot resolve the discrepancy, which probably arises due to uncertainties in the cross sections.

We find that the $^{49}$Ti/$^{49}$V data require a normalization of $N = (4.3 \pm 0.7) \times 10^{-5}$ mb and the $^{51}$V/$^{51}$Cr data require $N = (8.7 \pm 0.7) \times 10^{-5}$ mb. For a comparison again, Letaw et al. (1985) finds $N = (1.2 \pm 0.2) \times 10^{-4}$ mb.

Figure 1 depicts the two observations, $^{49}$Ti/$^{49}$V and $^{51}$V/$^{51}$Cr, with the model prediction for the optimal parameters derived above. The shaded regions correspond to the spectrum once solar wind modulation is added.\(^3\)

4.4. The Normalization Dependence on $z_t$ and $\tau_{arm}$ in a Spiral-arms Model

In a similar way to disk-like models, observational constraints on the secondary to primary ratios, such as B/C or sub-iron/iron ratios, imply that the normalization of the diffusion coefficient, $D_0$, varies when changing the geometry of the arms and/or the galaxy. Namely, for each pair of $z_t$ and $\tau_{arm}$, there is a corresponding value of $D_0$. While in the disk-like models we had to chose this normalization that will fit either the B/C ratio or the sub-iron/iron ratio, here in the spiral-arms model the same $D_0$ is consistent with both the B/C and sub-iron/iron data (Benyamin et al. 2016). Figure 5 shows a contour map of $D_0$ as a function of $z_t$ and $\tau_{arm}$. As expected, $D_0$ increases with both $z_t$ and $\tau_{arm}$.

The next step is to fix the attachment cross sections power-law index, $\mu = 1.8$. This value is consistent with the results of Letaw et al. (1985).

With the above values of $\mu$ and $D_0$, we can now proceed to obtain the optimal normalization of the attachment cross section, $N$, as a function of $z_t$ and $\tau_{arm}$. Figure 6 depicts contour maps of $N$ for the combined $\chi^2$ fit of the two data sets as a function of $z_t$ and $\tau_{arm}$. One can readily see that $N$ increases with $z_t$ but it decreases with $\tau_{arm}$.

We can quantify better the required normalization by using the form

$$N_{SA} = (7.98 \pm 0.02) \times 10^{-5} \times (\tau_{arm}/10 \text{ Myr})^{-0.278 \pm 0.008} \times (z_t/1 \text{ kpc})^{0.236 \pm 0.007} \text{ mb.}$$  (3)

5. Discussion and Summary

It is generally accepted that CR EC isotopes can be used to assess the importance of reacceleration in the ISM (Strong et al. 2007). Nonetheless, a comparison between model predictions and measurements of $^{51}$V/$^{51}$Cr and $^{49}$Ti/$^{49}$V gave inconsistent results, generally interpreted as arising from uncertainties in the nuclear spallation cross sections. Nebur et al. (2003) have shown that the typical 10%-20% uncertainty in the fragmentation cross sections (Webber et al. 2003) can explain away the discrepancy between the observations of the two isotopes. Specifically, they found that a reduction of the fragmentation cross sections of $^{49}$Ti by 15% was sufficient to resolve the discrepancy (see Figure 7). Previous analyses, however, considered axisymmetric models in which the CR source distribution is relatively smooth.

More recently, we developed a fully 3D CR diffusion model that not only considers that most CR acceleration takes place in the vicinity of spiral arms, but also that these arms are dynamic (Benyamin et al. 2014). One very important aspect of this model is that the PLD is different from the one found in standard disk-like models. In the latter, the PLD is typically close to being exponential. However, if most CRs arrive from a distance, such as from a spiral arm, then the PLD will exhibit a paucity of small path lengths (compare Figures 4–6 in Benyamin et al. 2014). Therefore, it was our goal to see whether a more realistic distribution of CR sources could

\(^3\) More details on the solar modulations can be found in Section 3.6 of Benyamin et al. (2014). Here, we use $\phi_{max} = 920 \text{ MV}$ and $\phi_{min} = 510 \text{ MV}$ which are the solar modulation values that correspond to the years of the CRIS measurements (Usoskin et al. 2011).
alleviate the discrepancy between the model predictions and the measurements of $^{51}\text{V}/^{51}\text{Cr}$ and $^{49}\text{Ti}/^{49}\text{V}$ ratios.

In this work, we studied the EC isotopes using the observations of $^{51}\text{V}/^{51}\text{Cr}$ and $^{49}\text{Ti}/^{49}\text{V}$ ratios, as well as an empirical fit to the electron attachment cross section of propagating nuclei. This fit is based on the results of Letaw et al. (1985), who derived the attachment and stripping cross section using experimental data from Wilson (1978) and Crawford (1979). They measured the timescales of both processes, which are much longer than the EC decay timescale; thus, we can neglect the stripping process and assume that when an EC isotope attaches to an electron, it will decay immediately. Letaw et al. (1985) also showed that the attachment cross section has an approximate power-law dependence on the energy and on Z, with respective power indices of $\mu = 1.8 \pm 0.1$ and $\nu = 4.5 \pm 0.1$, and a normalization of $N = (1.2 \pm 0.2) \times 10^{-4}$ mb (for $E = 500$ MeV and $Z = 1$).

We first found that the EC ratios in standard disk-like models are not only sensitive to the EC rates, but also modestly sensitive to the halo size. Specifically, the required cross section in disk-like models is $\sigma_{\text{EC}}(E, Z) = N(z_h) \times Z^{4.5} \times (E/500 \text{ MeV})^{-1.8}$, with the normalization roughly given by $N(z_h) = 8 \times 10^{-5}$ mb $\times (z_h/1 \text{ kpc})^{0.27}$.

We then found that EC in spiral-arms models can also constrain the geometry of the galactic arms in addition to the halo size. The required cross section also depends on the time since last spiral-arm passage. Its normalization should satisfy $N_{\text{arm}}(z_h, r_{\text{arm}}) = 7.98 \times 10^{-5}$ mb $\times (r_{\text{arm}}/10 \text{ Myr})^{-0.278} \times (z_h/1 \text{ kpc})^{0.236}$.

However, even with the added spiral arms, one cannot alleviate the discrepancy between the $^{51}\text{V}/^{51}\text{Cr}$ and $^{49}\text{Ti}/^{49}\text{V}$ measurements. This strengthens the claim that this discrepancy is due to the uncertainty in the spallation cross sections. Thus, improved spallation cross sections are required to use the EC CRs to constrain geometric properties of the diffusion models.

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