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Radioactive isotopes at relativistic energies: model predictions

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Abstract

Recent satellite experiments have provided data on abundances of the radioactive secondary isotopes ^{10}Be, ^{26}Al, ^{36}Cl, and ^{54}Mn in low energy cosmic rays. These isotopes are used as cosmic ray clocks and as a means to discriminate between models of cosmic ray propagation. We present calculations of surviving fractions of decaying isotopes in a wide energy range for a few galactic models including a leaky box model, flat-halo diffusion model, and a diffusion model with distributed reacceleration.

1 Introduction.

The abundance of radioactive secondary isotopes in cosmic rays depends on the density of the interstellar gas where these isotopes are produced in the course of fragmentation of primary energetic nuclei. The constant gas density n_{lb} is an explicit parameter in the homogeneous leaky box model, a much-used approximation for the description of cosmic ray transport in the Galaxy. Realistic non-homogeneous gas distributions are used in a more physical diffusion model. The production of a decaying secondary isotope is then determined by some effective gas density averaged over the distances of the order of $\sqrt{Dt}$ around an observer. Here D is the cosmic ray diffusion coefficient and t is the lifetime for decay including the relativistic factor; see Berezinskii *et al.* (1990) and Ptuskin & Soutoul (1998) for details. (In more exact terms D should be considered as a free parameter of the diffusion model since the actual interstellar gas density is known from astronomical observations.) Although the understanding that diffusion leads to the dependence of the effective gas density on t was advanced 25 years ago (Prishchep & Ptuskin, 1975), the first experimental evidences of this effect were obtained only recently after publication of the Voyager (Lukasiak *et al.* 1994) and in particular the Ulysses (Connell *et al.* 1997) data. In this regard the soon to be released results on radioactive isotopes from the CRIS experiment with great collecting power on board the ACE spacecraft are of decisive importance. The list of radioactive isotopes under the consideration includes ^{10}Be (the decay lifetime of an ion at rest is $2.3\cdot10^6$ yr), ^{26}Al ($1.3\cdot10^6$ yr), ^{36}Cl ($4.3\cdot10^5$ yr), ^{54}Mn($\sim 10^6$ yr), ^{14}C ($8.2\cdot10^3$ yr).

The satellite experiments with large statistics, including those mentioned above, operated at low energies. The investigations in a wide range of relativistic energies are also very important for the investigation of cosmic ray propagation. Such experiments may include direct measurements of isotope abundance. The balloon experiment ISOMAX on ^{10}Be at energies about 4 GeV/n (Streitmatter *et al.*1993) is an example. Another approach addresses the problem by using high precision data on the charge ratios. Webber & Soutoul (1998) recently presented the analysis of Be/B, Al/Mg, Cl/Ar, and Mn/Fe ratios measured on HEAO-3. The leaky box model and the diffusion model by Webber *et al.* (1992) were used in their work.

Below we present results of our calculations in the leaky box model and in the diffusion model with realistic gas distribution. We also consider the effect of particle reacceleration by interstellar turbulence.

2 Surviving fractions.

The measured abundance of radioactive isotope in cosmic rays may be conveniently expressed through the surviving fraction S defined as follows:

$$S = I(t)/I(t=\infty). \quad (1)$$

Here $I(t)$ is the cosmic ray intensity for radioactive isotope, $I(t = \infty)$ is the intensity for the same isotope considered stable.

The calculation of $I(t = \infty)$ is in fact the calculation of the content of stable secondary isotope. The escape length X_{lb} determines it in the leaky box model. Based on the data on B/C ratio, we use in the present work the following parameterization of the escape length as a function of particle magnetic rigidity R:

$$X_{lb} = 15b^{3/2}\ \text{g/cm}^2 \text{ at } R \leq 3.5\,\text{GV},\ X_{lb} = 15b^{3/2}\left(\frac{R}{3.5GV}\right)^{-0.6} \text{g/cm}^2 \text{ at } R > 3.5\,\text{GV}. \qquad (2)$$

Here b = v/c is the dimensionless particle velocity.

The flat halo diffusion model gives the same results for the calculation of stable secondary nuclei as the leaky box with the relation between parameters of these models given by the following approximate equation valid at not very large spallation cross sections (see Berezinskii *et al*. (1990) for details):

$$X_{lb} \approx \frac{mbcH}{2D} \text{ at } s << \frac{mH}{X_{lb}h}, \qquad (3)$$

where D is the cosmic ray diffusion coefficient, $m \approx 1.9$ mg/cm^2 is the total surface gas density of the galactic disk, H is the size of the cosmic ray halo, $h << H$ is the characteristic height of the gas distribution, and m is the mean mass of an atom in the interstellar gas.

Eqs. (2), (3) show that knowledge of the abundance of stable secondary nuclei in cosmic rays allows determination of the ratio D/H. With knowledge of the abundance of radioactive secondaries one can find D and H separately. The dependence of particle diffusion on energy $D \propto b / X_{lb}(E)$ follows from Eqs. (2), (3).

The modification of the diffusion model that includes distributed reacceleration in a process of particle diffusion in the interstellar medium allows reproduction of the measured abundance of stable secondaries with a single power law dependence $D \propto bR^{1/3}$. This scaling corresponds to particle scattering on MHD waves with the Kolmogorov spectrum. We do not make new calculations for stable secondaries in the model with reacceleration and use parameters found by Seo & Ptuskin (1994): escape length $X_e = 14(R/1\text{GV})^{-1/3}$ g/cm^2, Alfven velocity V_a = 20 km/s (see also Heinbach & Simon, 1995).

As pointed out earlier, the leaky box and the diffusion models are not equivalent for interpretation of data on radioactive nuclei. One can estimate $\sqrt{Dt} \approx 50 - 500$ pc for typical value of $D \approx 3{\cdot}10^{28}$ cm^2/s and for nonrelativistic isotopes listed above. The variations of the interstellar gas density are essential on these scales and must be incorporated in the calculations of the surviving fraction in the diffusion model. We use the same gas distribution as Ptuskin & Soutoul (1998). The diffusion coefficient is assumed to be independent of position. Berezinskii *et al.* (1990) and Ptuskin & Soutoul (1998) described the general approach to the calculations in the diffusion model. Details of the present calculations will be given in a separate paper.

Figures 1-3 present the calculated surviving fractions for the isotopes ^{10}Be, ^{26}Al, and ^{36}Cl as functions of particle interstellar energy in the diffusion model (solid lines) and in the leaky box model (dashed lines). The dash-dot lines show the effect of reacceleration in the diffusion model. The characteristic time of acceleration in the interstellar medium is large compared with the decay lifetimes and the difference between diffusion models with and without reacceleration is determined by the different dependence of diffusion coefficient on energy in these two cases. All calculations are made under the condition that the observed abundance of stable secondaries (the B/C ratio) is reproduced. The parameters are also fitted to the surviving fraction of ^{10}Be isotope $S(^{10}\text{Be}) = 0.19$ at interstellar energy 0.4 GeV/n as derived from the Ulysses data (Connell 1997). With the assumptions outlined the leaky box gas density is found to be equal to n_{lb} = 0.24 nucleon/cm^3, and the parameters of the diffusion model are $D = 5.2{\cdot}10^{28}$ cm^2/s at 1 GeV/n, and H = 7 kpc. (Notice that the age of cosmic rays with energies 1 GeV/n is $T_{lb} = X_{lb}/(\text{v}mn_{lb}) = 4{\cdot}10^7$ yr in the leaky box model while the average age of cosmic rays for an observer at the galactic disk is $T_d = H^2/3D = 9.7{\cdot}10^7$ yr in the diffusion model. Fragmentation and decay are not taken into account in these calculations of age.) The surviving fraction of ^{10}Be at all energies except 0.4 GeV/n and the surviving fractions of ^{26}Al and ^{36}Cl at all energies are now uniquely determined in each model. It is clear from Figure 1 that the

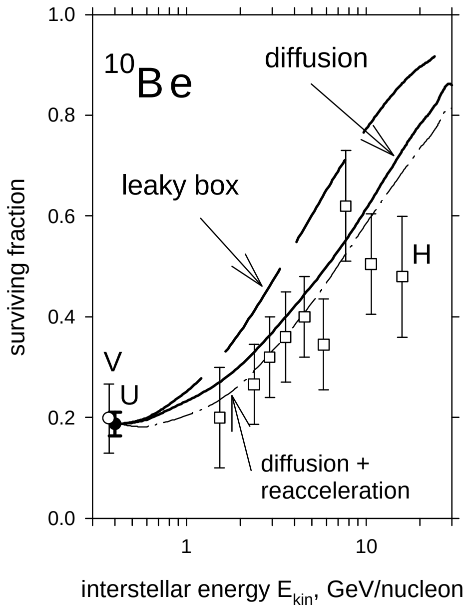

Figure 1: The surviving fraction of ^{10}Be. The data from Ulysses (U), Voyager (V), and HEAO-3 (H, from Webber & Soutoul 1998) experiments.

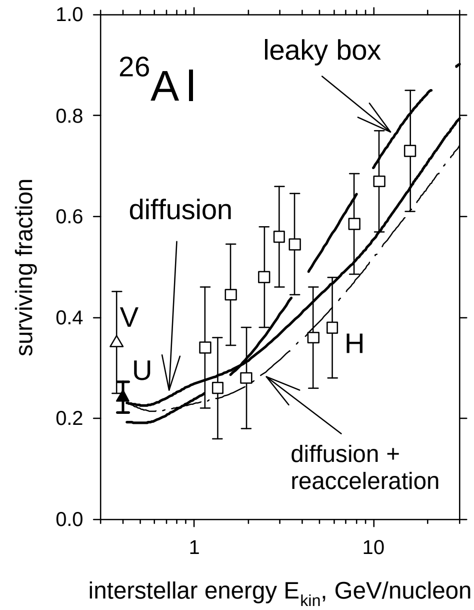

Figure 2: The same as Figure 1 but for ^{26}Al.

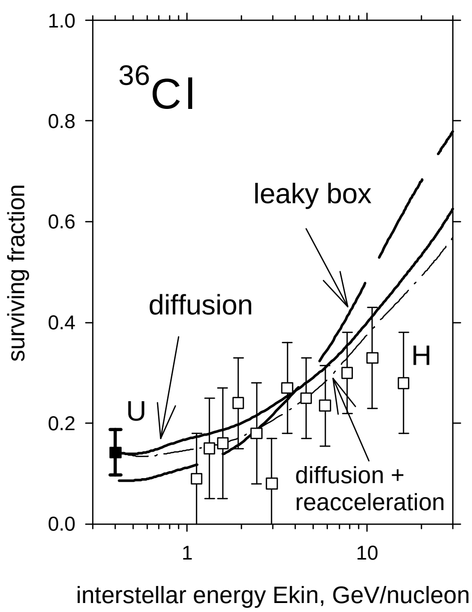

Figure 3: The same as Figure 1 but for ^{36}Cl.

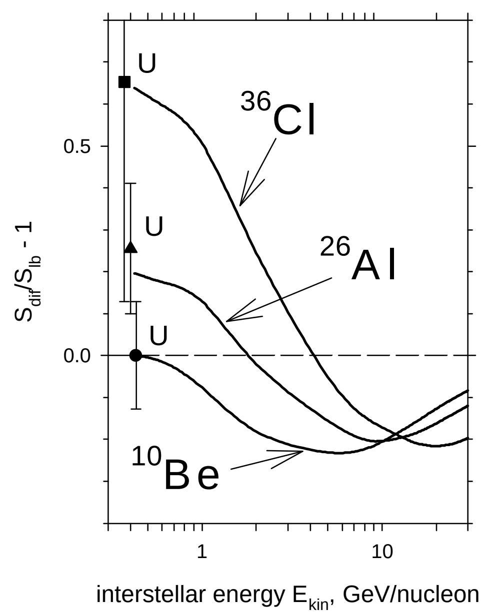

Figure 4: The calculated ratios of surviving fractions S_{dif}/S_{lb}-1 (solid lines), and the low-energy ratios S_{obs}/S_{lb}-1 found from the Ulysses data (U).

surviving fraction $S(^{10}Be)$ fixed at 0.4 GeV/n increases faster with energy in the leaky box model than in the diffusion models. This is a clear evidence of the dependence of effective gas density on the decay time in the diffusion model. For the same reason the diffusion curves on Figures 2, 3 for ^{26}Al and ^{36}Cl, the isotopes with shorter lifetimes than ^{10}Be, start at higher values of surviving fraction at 0.4 GeV/n than the leaky box curves and cross them at some larger energies. Figure 4 shows the calculated difference $(S_{dif}-S_{lb})/S_{lb}$ between the diffusion and the leaky box models. The data points show the difference $(S_{obs}-S_{lb})/S_{lb}$ between the Ulysses data and the leaky box model predictions.

The surviving fractions at 0.4 GeV/n calculated from the isotope measurements on Ulysses and Voyager are shown on Figures 1-4. The error bars present the statistical errors alone. The surviving fractions derived at higher energies by Webber & Soutoul (1998) from the elemental ratios measured in the HEAO-3 experiment are shown on Figures 1-3. They are not shown in Figure 4 because of large errors.

3 Conclusion.

It is not excluded that the potentialities of low energy satellite studies of radioactive secondary isotopes may be exhausted for some period after the ACE experiment. The measurements in an extended energy range are very useful because the Lorenz factor changes the decay time of a relativistically moving isotope. However the high-accuracy measurements at relativistic energies are difficult and need good justification by the modeling of cosmic ray propagation in the Galaxy. It is why we fulfilled the calculations of surviving fractions of radioactive isotopes presented in Figures 1-4.

It is evident from Figures 1-4 that the diffusion model is favoured over the leaky box model at low energies where accurate Ulysses and Voyager data exist. The inclusion of weak distributed reacceleration does not significantly change this conclusion. The situation at relativistic energies is not clear because of large errors in the data on elemental ratios.

For the proposed ISOMAX balloon experiment at about 4 GeV/n (Streitmatter *et al.*, 1993) the diffusion model (respectively the leaky box model) predicts $S(^{10}Be) = 0.42$ (respectively 0.54) assuming that $S(^{10}Be) = 0.19$ at 0.4 Gev/n. The expected statistical error for a 10 days flight is about +/-0.05 which may be good enough for distinguishing between two popular models.

The old approach based on the study of elemental ratios (see e.g. Shapiro & Silberberg 1970) revived recently by Webber & Soutoul (1998) is also competitive with the isotope experiments.

References

Berezinskii, V.S. *et al.* 1990, Astrophysics of Cosmic Rays (North-Holland)
Connell, J.J. 1997, 25th ICRC, Durban 3, 385
Connell, J.J., DuVernois, M.A., & Simpson, J.A. 1997, 25th ICRC, Durban 3, 397
Heinbach, U. & Simon, M. 1995, ApJ 441, 229
Lukasiak, A., McDonald, F.B., Webber W.R. 1994, ApJ 430, L72
Prishchep, V.L. & Ptuskin, V.S. 1975, Astrophys. Space Sci. 32, 265
Ptuskin, V.S. & Soutoul, A. 1998, A&A 337, 859
Seo, E.S. & Ptuskin, V.S. 1994, ApJ 431, 705
Shapiro, M.M. & Silberberg, R. 1970, An. Rev. Nucl. Part.Sci. 20, 323
Streitmatter, R.E. *et al.* 1993, 23rd ICRC, Calgary 2, 623
Webber, W.R., Lee, M.A., & Gupta, M. 1992, ApJ 390, 96
Webber, W.R. & Soutoul, A. 1998, ApJ 506, 335