THE ISOTOPIC COMPOSITION OF COSMIC RAY CHLORINE

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ABSTRACT

The isotopic composition of galactic cosmic ray chlorine ($E \simeq 225$ MeV/amu) has been studied using the high energy cosmic ray experiment on the ISEE-3 spacecraft. The abundances of ^{35}Cl and ^{37}Cl are found to be consistent with the secondary production expected from a propagation model developed to account for both light and sub-iron secondaries. An upper limit on the abundance of the radioactive isotope ^{36}Cl (halflife $\simeq$ 0.3 Myr) is used to set a lower limit on the confinement time of cosmic rays of $\sim$1 Myr.

1. Introduction. Studies of the abundances of secondary cosmic ray nuclides at low energies (<500 MeV/amu) have shown that no single exponential distribution of pathlengths is adequate for the simultaneous interpretation of both the light secondaries, Li, Be, and B, and the sub-iron secondaries, Sc through Mn (see [1], and references therein.) As a consequence, more elaborate models involving pathlength distributions which are exponential for long pathlenghts, but which are deficient in short pathlengths (<1-2 g/cm^2), have been developed [1]. The necessity of introducing a second parameter (the amount of truncation) in order to explain the abundances of two groups of secondary nuclides raises the question of whether the propagation model is generally applicable or simply an empirical fit with enough free parameters to permit agreement with a relatively small body of data. This question is of considerable practical importance since such propagation models are used to calculate the secondary corrections needed to derive cosmic ray source abundances from the observed abundances of nuclides of intermediate mass, including the isotopes of neon, magnesium, and silicon, which are found to differ significantly from solar system composition. If the propagation model used did not accurately predict the secondary production of species of mass intermediate between the light elements and the sub-iron elements, sizeable errors in the derived source composition would result.

It is important to directly check the adequacy of accepted propagation models by testing their predictions of abundances of intermediate mass secondary nuclides. However, few elements between Z=10 and Z=20 are clearly dominated by secondaries. Observations of the elemental abundance of cosmic ray chlorine (Z=17) suggest that the isotopes ^{35}Cl and ^{37}Cl may both be dominantly secondary, but direct measurements of the isotopic composition of chlorine are needed to check whether this is indeed the case.

In addition, the radioactive isotope ^{36}Cl (halflife $\simeq$ 0.3 Myr) is one of the relatively small number of nuclides with $Z \lesssim 28$ which beta decay on a time scale suitable for studying the confinement time distribution of cosmic rays. Since its halflife is shorter than that of the other beta-active nuclides which have previously been investigated (^{10}Be

1.6 Myr; ^{26}Al, 0.87 Myr), it is useful for investigating the density of the matter encountered by cosmic rays during the final few percent of the time required for transport to the vicinity of the Earth.

2. Observations. We have investigated the isotopic composition of galactic cosmic ray chlorine using data from the high energy cosmic ray experiment on the ISEE-3 spacecraft. These data, collected between August 1978 and April 1981, cover an energy interval from 140 to 360 MeV/amu. The instrument consisted of a silicon solid state detector telescope used to measure energy losses and total energy and a gas proportional drift chamber used to measure cosmic ray particle trajectories. The mass uncertainty is dominated by trajectory errors, and therefore increases rapidly with the angle of the particle's incidence, measured from the normal to the detector surfaces. In previous studies of the isotopic composition of elements with $Z<16$ it was possible to restrict the analysis to events with incidence angles less than some maximum chosen to permit nearly complete separation of the individual mass peaks while retaining reasonable statistical accuracy. For $16<Z<26$ however, the combination of poorer mass resolution (which is approximately proportional to mass) and small natural abundances does not permit the selection of a fully resolved data set. Figure 1 shows the chlorine mass histogram obtained by utilizing data with incidence angles of 20° or less. Peaks corresponding to masses of 35 and 37 are evident, while ^{36}Cl is significantly less abundant and is not resolved from the other isotopes.

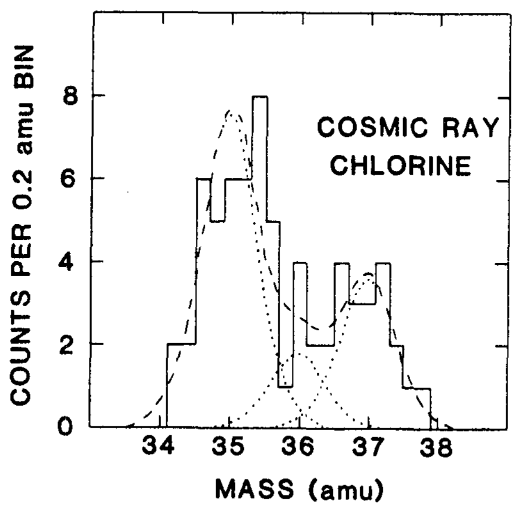

Figure 1. Observed chlorine mass histogram is shown together with the fitted mass distribution (dashed curve) and the three isotope peaks of which it is composed (dotted curves.)

Quantitative evaluation of the isotopic abundances (especially of ^{36}Cl) requires a detailed understanding of the instrument's response to a mono-isotopic particle population. In order to obtain such an understanding, we have studied the dependence of mass resolution on incidence angle ($\theta<20°$) for a number of abundant nuclides which are resonably well resolved from adjacent isotopes. The angular dependence is well fit by

$$\sigma_M = \sqrt{(a^2 + b^2 \cdot \sin^2 2\theta)}.$$

This form, with $b \propto M$, is expected as a result of the fact that the mass resolution is dominated by trajectory uncertainties. The dependence of the coefficients a and b on the mass (or, equivalently, the charge) of the nuclide was studied by fitting this form for stable nuclides with mass numbers between 6 and 34, and for ^{45}Sc and ^{56}Fe. These coefficients were found to depend smoothly on mass over the entire range studied, and the b coefficient was proportional to mass, as expected.

The abundances of the three chlorine isotopes were obtained using a maximum likelihood fit to the observed distribution of calculated masses, assuming the above functional dependence of mass resolution on incidence angle. The values of a and b obtained for chlorine agree, within errors, with the trend found for the other nuclides studied. The fitted mass distribution, together with the three isotope peaks of which it is composed, is shown superimposed on the observations in Figure 1. The derived isotope fractions, when combined with our observation of the element ratio Cl/S = 0.20 ± 0.02, yields the following near-Earth abundance ratios: ^{35}Cl/S = 0.116 ± 0.024, ^{36}Cl/S < 0.048, and ^{37}Cl/S = 0.058 ± 0.016. The errors shown are one standard deviation, and the ^{36}Cl upper limit is at the 84% confidence level. The element sulfur was chosen for the normalization since it is the nearest dominantly primary element to chlorine.

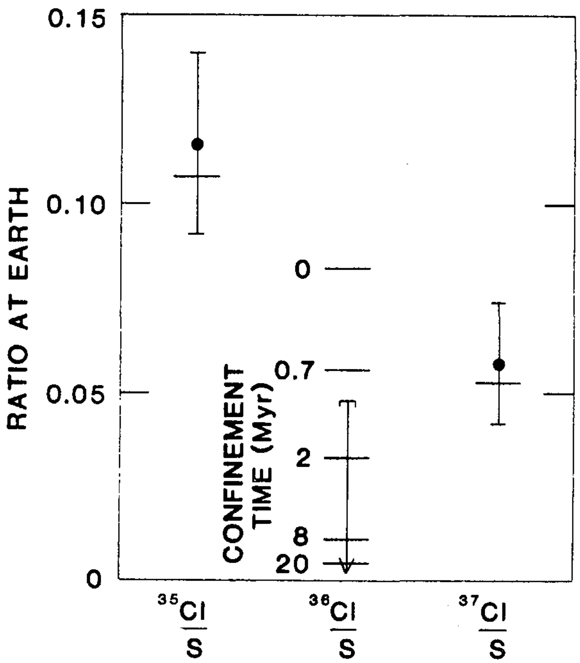

Figure 2. Observed chlorine isotope abundances (relative to the elemental sulfur abundance) are compared with the results of a propagation calculation (horizontal lines.) For ^{36}Cl the calculation depends on the cosmic ray confinement time.

3. Discussion. Figure 2 compares the observed abundance ratios with the predictions of a propagation model which is consistent with both light and sub-iron secondary element abundances (specifically, the ratios B/C and Sc+V/Fe) in low energy (∿100-300 MeV/amu) cosmic rays. This model employs a nested leaky box with mean pathlengths of 1.5 and 3.0 g/cm^2 (with H:He=10:1) and standard cross section formulae. Solar modulation effects were taken into account using a force field approximation with mean energy loss Φ=325 MeV/amu (for A=2Z nuclides.) We have assumed that chlorine is entirely absent at the source, although the calculated abundances near Earth are not changed significantly if one assumes that the source abundance of chlorine is comparable to its solar system value (Cl/S=0.01). As seen in the figure, the ^{35}Cl and ^{37}Cl abundances are well fit by this model.

The calculation of the ^{36}Cl abundance at Earth depends on the assumed cosmic ray confinement time (or, equivalently, the assumed density of interstellar gas) since this parameter determines the fraction of the ^{36}Cl which decays between the time it is produced by spallation and the time it is observed at Earth. As previously pointed out [3], the ^{36}Cl abundance in the absence of beta decay is a sizeable fraction of the chlorine element abundance, so this isotope is useful for studying the cosmic ray confinement time in spite of the fact that its halflife is significantly shorter than that time (as determined from ^{10}Be), $T_{1/2}/\tau_{esc} \simeq 0.04$.

Figure 2 includes calculated values of the ^{36}Cl/S ratio for various values of the cosmic ray confinement time. Our lower limit on the near-Earth abundance of ^{36}Cl implies a cosmic ray confinement time greater than $\sim$1 Myr. This limit is consistent with the confinement time values we previously reported based on the abundances of ^{10}Be [4] (8.4 [+4.0, -2.4] Myr), and ^{26}Al [5] (9 [+20, -6.5] Myr.)

The limited statistics and resolution in the present observations of ^{36}Cl do not allow a very stringent test of the homogeneity of the matter in the cosmic ray confinement volume. However, the consistency of both the interstellar pathlength distribution and the confinement time deduced from the observed chlorine isotopic abundances with those previously obtained from other stable and unstable secondary nuclide abundances indicate that no major differences exist in the confinement of different elements, at least in the range $3 \lesssim Z \lesssim 26$.

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