

THE ISOTOPIC COMPOSITION OF COSMIC RAY CALCIUM

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ABSTRACT

Data from the high energy cosmic ray experiment on the ISEE-3 spacecraft have been used to study the isotopic composition of cosmic ray calcium at an energy of ~ 260 MeV/amu. The arriving calcium is found to consist of $(32 \pm 6)\%$ ^{40}Ca . A propagation model consistent with both the light and the sub-iron secondary element abundances was used for the interpretation of the observed calcium composition. The measured $^{42}\text{Ca}+^{43}\text{Ca}+^{44}\text{Ca}$ abundance is consistent with the calculated secondary production, while the ^{40}Ca abundance implies a source ratio of $^{40}\text{Ca}/\text{Fe} = (7.0 \pm 1.7)\%$.

1. Introduction. In the cosmic radiation, most of the elements in the sub-iron region ($17 \leq Z < 26$) are predominantly secondary in origin, resulting from the fragmentation of heavier cosmic ray nuclei during propagation from the source to the Earth. Calcium is one exception to this pattern, having a significant contribution from primary cosmic rays, particularly for the isotope ^{40}Ca , the dominant isotope ($\sim 97\%$) of solar system calcium [1]. In this paper, we present new measurements of the galactic cosmic ray calcium isotopic composition and compare them with measurements made by other experimenters and the values found for solar system material.

2. Data. The observations reported here were taken with the high energy isotope experiment on the ISEE-3 spacecraft during the time period from August 1978 to April 1981. The energy range for calcium is approximately 170 to 380 MeV/amu with an average of approximately 260 MeV/amu. Cuts were made on the data to eliminate nuclear interactions in the instrument and to choose only those events which have well determined trajectories. In addition, only those particles having incident angles of less than 15 degrees with respect to the detector normal were used in the data set presented here in order to obtain the best mass resolution compatible with the desired statistical accuracy.

For calcium, a direct measure of the instrument resolution can be obtained from a comparison with the adjacent element, scandium, which has a single stable isotope, ^{45}Sc . The scandium mass distribution can be used as a measure of both the absolute mass scale and the resolution expected at calcium.

Figure 1(a) shows the scandium mass distribution in 0.25 amu bins, along with a best fit Gaussian curve. The Gaussian has a standard deviation of 0.49 amu and the histogram has been adjusted to be centered at mass 45. The difference between the calculated mean mass and the true mass was 1.1 amu, and is simply an artifact of systematic errors in the mass calculation. This value is consistent with the smoothly varying trend seen for lighter elements and for iron. Figure 1(b) shows the cal-

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cium distribution in 0.25 amu bins, again with a best fit distribution superimposed. This fitted distribution is a superposition of five Gaussian peaks (corresponding to isotopes of mass 40 through 44) with center-to-center spacings of 1 amu and equal widths. The common width and the position of the mass 40 peak were allowed to vary in the fit along with the individual abundances. The deduced resolution was 0.53 amu and an offset of 1.07 amu was needed to center the mass 40 peak.

Although the mass resolution achieved is insufficient to cleanly resolve ^{42}Ca , ^{43}Ca , and ^{44}Ca , the relative lack of ^{41}Ca permits separation of the dominantly primary ^{40}Ca from the dominantly secondary ^{42}Ca , ^{43}Ca and ^{44}Ca . Comparison with the scandium mass distribution clearly demonstrates that the structure seen in the calcium histogram is due to actual abundance variations and not just statistical fluctuations since the width of the ^{45}Sc peak, 0.49 amu, is significantly less than the overall width of the calcium distribution and is consistent with the resolution determined from the calcium data. In addition, the scandium permits an unambiguous determination of the absolute mass scale verifying that ^{40}Ca is assigned the correct mass.

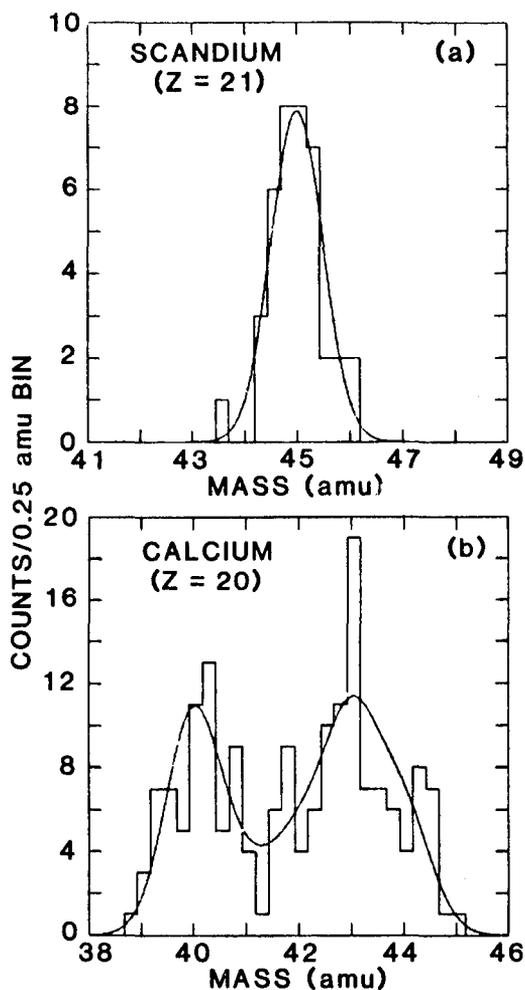


Figure 1

3. Discussion. Because ^{42}Ca , ^{43}Ca , and ^{44}Ca are not clearly separated in this data set, determination of their individual abundance values requires a more detailed analysis of the resolution systematics. However, a way of viewing these data which is less dependent on the details of the peak shapes is to divide the calcium into primary species (^{40}Ca) and secondaries (^{42}Ca , ^{43}Ca and ^{44}Ca) since the low abundance of ^{41}Ca permits resolution at this scale. Our data imply an arriving cosmic ray calcium composition of $(32 \pm 6)\%$ ^{40}Ca and $(60 \pm 6)\%$ 'secondary group', as defined above. Since the ^{41}Ca could be expected to be sensitive to the exact peak shape used, no value is reported here.

These isotope fractions are plotted in Figure 2, along with the results reported by other experimenters [2, 3, and 4]. Since the New Hampshire [3] and Minnesota [2] groups presented individual isotopic abundances, the uncertainties shown for their $^{42}\text{Ca}+^{43}\text{Ca}+^{44}\text{Ca}$ measurements are estimated from the individual errors that they reported. Additionally, Tarlé *et al.* [4] did not present an explicit $^{40}\text{Ca}/\text{Ca}$ ratio. The value used here is the result of counting events on their calcium mass histogram. As can be seen from Figure 2, there is reasonable agree-

ment between experiments when the data are presented in this way.

Also shown in Figure 2 (dashed line) are the results of a cosmic ray propagation calculation employing a nested leaky box model with mean escape lengths of 1.5 g/cm^2 for the inner leaky box and 3.0 g/cm^2 for the outer box ($\text{H:He} = 10:1$). Solar modulation is taken into account using a numerical integration based on the method of Fisk [5]. Solar system isotopic composition [1] was assumed for elements with $Z \geq 19$ in the cosmic ray source, and source elemental abundances were chosen to reproduce the elemental abundances observed near Earth at 70-280 MeV/nucleon [6]. The pathlength values used were those needed to simultaneously reproduce the observed B/C and the $(\text{Sc}+\text{V})/\text{Fe}$ ratios at these energies.

The shaded areas on the figure indicate the fraction of each group which is primary. As can be seen, the division into ^{40}Ca and $^{42}\text{Ca}+^{43}\text{Ca}+^{44}\text{Ca}$ provides a very clean separation between primary and secondary calcium.

This propagation model, based on light and sub-iron secondary elements, is also compatible with the observed abundance of calcium secondaries (Figure 2). The present observations imply that the ratio $^{42}\text{Ca}+^{43}\text{Ca}+^{44}\text{Ca}/^{40}\text{Ca}$ in the cosmic ray source does not exceed its solar system value (0.03) by more than a factor of ~ 30 . Although our measured abundance of this secondary group does not require a finite source abundance of any calcium isotope other than ^{40}Ca , separation of this group into its constituent isotopes is required to firmly establish this conclusion.

Because the calcium elemental abundance observed at Earth is 60% secondary while the isotope ^{40}Ca is only 4% secondary, the use of the calcium isotope information can significantly reduce the uncertainties involved in deriving the source abundance of calcium. If we ignore the isotope information and employ only the elemental abundances of [6], we find that the source Ca/Fe ratio is $(8.2 \pm 7.8)\%$, where the uncertainty includes the effects both of observation errors and of propagation errors [7]. The latter source of uncertainty, due mostly to assumed 35% correlated errors in fragmentation cross sections, is found to dominate. If the ^{40}Ca isotope fraction is used in conjunction with the elemental abundances, we obtain, at the source, $^{40}\text{Ca}/\text{Fe} = (7.0 \pm 1.7)\%$. The relative uncertainty in this source ratio is only 24%, as compared with the 95% uncertainty in the ratio obtained using elemental abundances alone. Furthermore, the uncertainty in our deduced $^{40}\text{Ca}/\text{Fe}$ source ratio is dominated by the observation errors (rather than by uncertainties in the propagation calculation), so future improvements in the resolution and statistical accuracy of calcium isotope measurements will further improve the accuracy of the deduced ^{40}Ca source abundance. In Table 1 we compare our value of the $^{40}\text{Ca}/\text{Fe}$ source abundance ratio with values reported by

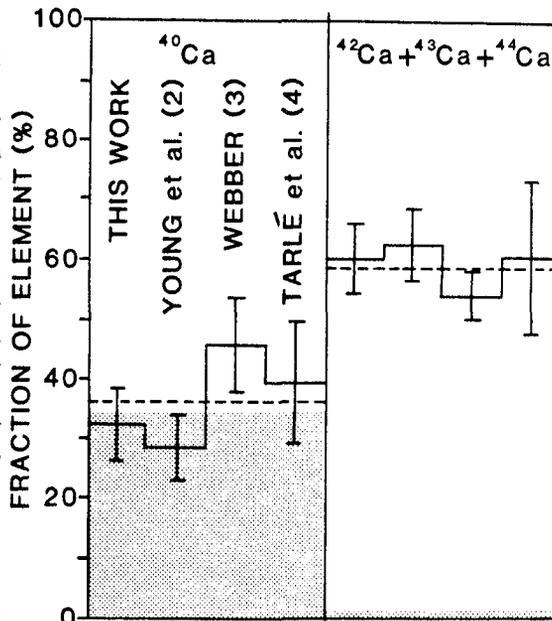


Figure 2

other investigators. While these values are all in reasonable agreement, one must exercise caution in comparing them because the specifics of the propagation models and error calculations used by the various authors differ.

The ratios of cosmic ray source elemental abundances (GCRS) to the corresponding solar system values (SS) have been found to be reasonably well organized by the first ionization potential of the element (e.g. [8], and references therein), although other possible ordering parameters (such as volatility [9]) have been proposed. By combining our $^{40}\text{Ca}/\text{Fe}$ source ratio with the value of this ratio in the solar system (6.73% [1]), we find $(^{40}\text{Ca}/\text{Fe})_{\text{GCRS}}/({}^{40}\text{Ca}/\text{Fe})_{\text{SS}} = 1.04 \pm 0.25$. Two general functional forms have been suggested for representing the dependence of such ratios on first ionization potential. The first is an exponential dependence of the form $\text{GCRS}/\text{SS} \propto \exp(-I/I_0)$, while the second is a step function where all elements with low first ionization potential ($I \lesssim 9$ eV) have one value and all those with high first ionization potential have a single, lower value. Calcium has a first ionization potential of 6.1 eV and for iron the value is 7.9 eV. Our present results are thus consistent with the step-function dependence. They are consistent with an exponential dependence only if a relatively low value of the parameter I_0 is used. Brewster et al. [10] have reported the results of two different exponential fits. One, excluding the light noble gas elements, has $I_0 = 3.47$ eV, and implies that the GCRS $^{40}\text{Ca}/\text{Fe}$ ratio should be 1.66 times the solar system value. The other has $I_0 = 5.6$ eV and implies that the $^{40}\text{Ca}/\text{Fe}$ enhancement should be 1.37. These two predictions exceed our deduced value by 2.5 and 1.3 standard deviations, respectively. While discrepancies at this level for a single element are not sufficient to rule out such exponential dependence on first ionization potential, they do suggest that extreme exponential dependencies are unsatisfactory in this case or that some other ordering parameter may be more appropriate.

TABLE 1

Derived Values of $^{40}\text{Ca}/\text{Fe}$ in the Cosmic Ray Source	
Value	Reference
7.0 ± 1.7 %	this work
6.2 ± 1.1 %	2
8.8 ± 1.6 %	3
5.9 ± 1.9 %	4

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