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Satellite Measurements of the Isotopic Composition of Galactic Cosmic Rays

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The individual isotopes of galactic cosmic ray Ne, Mg, and Si at ~ 100 MeV/nucleon have been clearly resolved with an rms mass resolution of ~ 0.20 amu. Our results suggest that the cosmic ray source is enriched in ^{22}Ne, ^{25}Mg, and ^{26}Mg when compared to the solar system. In particular, we find $(^{25}\mathrm{Mg} + {}^{26}\mathrm{Mg})/{}^{24}\mathrm{Mg} = 0.49^{+.23}_{-.14}$ compared to the solar system value of 0.27, suggesting that the cosmic ray source and solar system material were synthesized under different conditions.

1. Introduction. Galactic cosmic rays provide a sample of matter from outside the solar system, which, in view of its younger age and possible association with supernovae, may have experienced a different nucleosynthetic history than solar system material. Because the elements neon, magnesium and silicon each possess more than one relatively abundant isotope and because they are the result of several nucleosynthetic processes, they are excellent choices for investigating possible isotopic differences between the cosmic ray source and the solar system.

Neon is the first element for which there is strong evidence for an anomalous galactic cosmic ray isotopic composition. Several recent studies (Fisher et al. 1976; Prezler et al. 1975; Garcia-Munoz et al. 1979; Greiner et al. 1979) find a several-fold excess of ^{22}Ne at the cosmic ray source when compared to the Cameron (1973) solar system compilation (^{20}Ne/^{22}Ne = 8.2) or to solar flare nuclei (^{20}Ne/^{22}Ne = $7.6^{+2.0}_{-1.8}$, Mewaldt et al. 1979; see also Dietrich and Simpson 1979); or to the solar wind (^{20}Ne/^{22}Ne = 13.7, Geiss 1972).

In this paper we report the first cosmic ray observations with clearly resolved individual isotopes of Ne, Mg and Si. These observations cover the energy interval from ~ 30 to ~ 180 MeV/nucleon, where a mass resolution of $\sigma \simeq 0.20$ amu is achieved.

2. Observations. The Caltech Heavy Isotope Spectrometer Telescope (HIST) is carried on ISEE-3, launched 8/12/78. This study includes quiet-time data from launch until 12/1/78. The HIST telescope (Althouse et al. 1978) consists of an array of solid state detectors, including a pair of two-dimensional position-sensitive detectors which determine individual particle trajectories, thereby leading to significant improvement in isotope resolution over previous cosmic ray instruments.

The method of resolving isotopes in HIST has been discussed by Mewaldt et al. (1979). In this study we used the outputs of the last three triggered detectors to make two separate determinations of the charge Z and the mass M for each event. Those events for which the two mass determinations were consistent to within ± 5% were accepted for further analysis and a best estimate for M was computed from a weighted average of the two individual mass determinations. Only 4 events were eliminated by this consistency test. Figure 1a shows mass histograms obtained in accelerator calibrations of HIST at the Bevalac, while Figure 1b shows the flight data from the same energy range. Both data sets have been analyzed in exactly the same manner, using identical selection criteria and instrument calibrations. The Bevalac data therefore provide absolute knowledge of the mass scale. The average mass resolution in the calibration data is $\sigma_m \approx 0.18$ amu, while in the flight data $\sigma_m \approx 0.20$ amu.

We determined the relative isotopic abundances using two-dimensional maximum likelihood techniques that take into account both mass determinations for each event. These abundances were then corrected for small energy interval differences, assuming modulated energy spectra $dJ/dT \propto T^{0.6}$ at 1 AU, as suggested by measurements by Garcia-Munoz et al. (1977a). Table 1 summarizes our measurements at 1 AU. In Figure 2 we compare our observations with others, and with the expected isotopic fractions for a cosmic ray source of solar system isotopic composition.

Other investigations measured the mean mass of neon (Fisher et al. 1976; Dwyer 1978), or the $^{22}Ne/^{20}Ne$ ratio (Prezler et al. 1975; Garcia-Munoz et al. 1979; Greiner et al. 1979), without determining the ^{21}Ne abundance. To include these measurements in Figure 2 we assumed a ^{21}Ne fraction of 0.11, as is calculated assuming negligible ^{21}Ne at the source. Our observations are consistent with those studies that find excess ^{22}Ne in the cosmic rays. The mean mass measurements of Fisher et al. (1976) and of Dwyer (1978) do not yield unambiguous individual isotopic abundances for Mg and Si, but their results are generally consistent with a source having solar system isotopic composition. In

TABLE 1 - FRACTIONAL ISOTOPIC ABUNDANCES*

Isotope	Observed Fraction†	Cosmic Ray Source Fraction†	Solar System Fraction‡
^{20}Ne	$0.62^{+.06}_{-.11}$	$0.75^{+.13}_{-.14}$	0.889
^{21}Ne	$0.07^{+.07}_{-.03}$	< 0.06	0.003
^{22}Ne	$0.31^{+.08}_{-.08}$	$0.25^{+.14}_{-.13}$	0.108
^{24}Mg	$0.60^{+.04}_{-.07}$	$0.67^{+.07}_{-.09}$	0.787
^{25}Mg	$0.19^{+.06}_{-.04}$	$0.16^{+.07}_{-.06}$	0.101
^{26}Mg	$0.21^{+.06}_{-.04}$	$0.17^{+.08}_{-.06}$	0.112
$^{25}Mg + ^{26}Mg$	$0.40^{+.07}_{-.04}$	$0.33^{+.09}_{-.07}$	0.213
^{28}Si	$0.86^{+.03}_{-.11}$	$0.91^{+.03}_{-.12}$	0.922
^{29}Si	$0.07^{+.07}_{-.03}$	$0.04^{+.08}_{-.02}$	0.047
^{30}Si	$0.07^{+.08}_{-.03}$	$0.05^{+.07}_{-.03}$	0.031
$^{29}Si + ^{30}Si$	$0.14^{+.11}_{-.03}$	$0.09^{+.12}_{-.03}$	0.078

* The fraction relative to the total element abundance.

† 68% confidence intervals

‡ Cameron (1973)

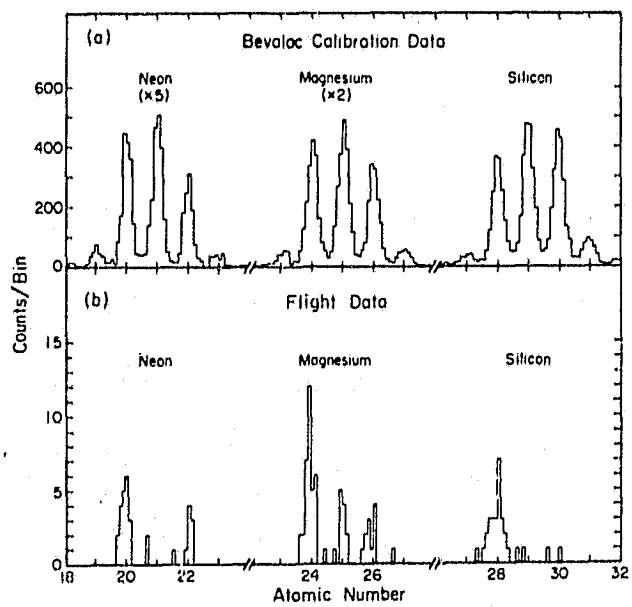

Fig. 1. Mass histograms of (a) Bevalac calibration data and (b) flight data for ~ 30 to ~ 180 MeV/nucleon Ne, Mg and Si isotopes. In addition to stable isotopes, the calibration data include short-lived radioactive species.

contrast, our results suggest excesses of both ^{25}Mg and ^{26}Mg at the source. In addition, Simpson et al. (1977) have reported both isotopic fractions and mean mass measurements for Ne, Mg and Si at ~ 3 g/cm^2 residual atmosphere which they concluded were consistent with a solar system source composition.

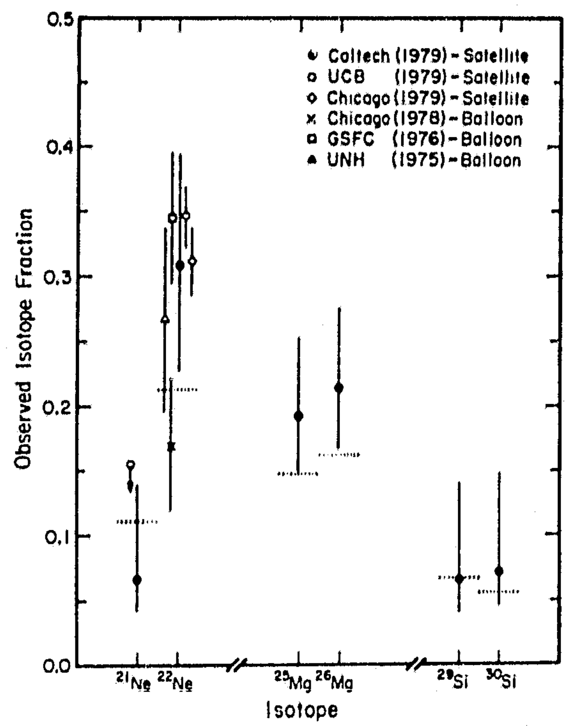

Fig. 2. A comparison of fractional isotopic abundances. The dotted lines are calculated for a solar system source. Data references: UCB (Greiner et al. 1979); Chicago 1979 (Garcia-Munoz et al. 1979) Chicago 1978 (Dwyer 1978); GSFC (Fisher et al. 1976); UNH (Prezler et al. 1975).

3. Interpretation. In order to interpret our observations we performed interstellar propagation and solar modulation calculations. We assumed a standard leaky-box propagation model with an escape mean free path of $\lambda = 5.5$ g/cm^2 (Garcia-Munoz et al.1977b) and used the semi-empirical cross sections of Silberberg et al. (1976). The element source abundances ($6 \leq Z \leq 28$) were adjusted to fit measurements by Garcia-Munoz et al. (1977a, 1977c) and Webber and Lezniak (1978). The source was assumed to have solar system isotopic composition except for Ne, Mg and Si, where the isotopic fractions were varied for comparison with the observations.

In order to calculate the effect of solar modulation on the relative abundances of isotopes with different charge to mass ratios we evaluated numerical solutions of the Fokker-Planck equation. A convenient measure of the degree of solar modulation is the energy-loss parameter Φ measured in MeV/nucleon (Gleeson and Axford 1968). For an assumed source spectrum $dJ/dT \propto (T + E_0)^{-2.6}$, where T is the kinetic energy in MeV/nucleon, Garcia-Munoz et al. (1977b) find $\Phi \simeq 220$ MeV/nucleon for 1973-1976 with $E_0 = 400$ MeV/nucleon. We used this spectrum and $\Phi = 300$ MeV/nucleon for late 1978. For $E_0 = 400^{+200}_{-150}$ MeV/nucleon, and corresponding values of $\Phi = (300 \pm 100)$ MeV/ ucleon, we find that the 1 AU $^{22}Ne/^{20}Ne$ ratio at ~ 100 MeV/nucleon is $(19 \pm 6)\%$ greater than the interstellar value at $T = (100 + \Phi)$ MeV/nucleon. Solar modulation effects on the other isotopic ratios considered here are correspondingly smaller than for $^{22}Ne/^{20}Ne$.

Figure 3 shows the predicted $^{25}Mg + ^{26}Mg$ fraction at 1 AU as a function of the source fraction for various combinations of Φ and λ, assuming that ^{26}Al decays. Also indicated are the 68% (1σ) and 90% (1.65σ) confidence intervals, as derived from the maximum likelihood analysis. Note that our observations imply a $^{25}Mg + ^{26}Mg$ source fraction of $0.33^{+.09}_{-.07}$, significantly greater than the solar system fraction of 0.21. Using similar curves for the individual Ne, Mg and Si isotopes, we obtain the source composition in Table 1. The uncertainties in Table 1 include statistical uncertainties, as well as uncertainties associated with propagation and modulation (typically $\sim .01$), as derived from the envelope of the calculated curves for $\lambda = (5.5 \pm 1)$ g/cm^2 and $\Phi = (300 \pm 100)$ MeV/nucleon (see, e.g., Figure 3).

An additional uncertainty in the propagation calculations is associated with cross section uncertainties. Since the observed ^{21}Ne should be almost entirely of secondary origin, ^{21}Ne observations provide a check that the propagation model has not grossly underestimated the secondary contributions to the other nuclei. We find from Stone and Wiedenbeck (1979) that systematic underestimates of a number of ^{22}Ne-production cross sections by a factor of > 3 relative to ^{21}Ne production would be required to account for the observed ^{22}Ne excess, while ^{25}Mg and ^{26}Mg excesses of a factor of ~ 1.8 would require systematic errors of a factor of 2 to 3. We feel that such large systematic errors in the relative cross sections are very unlikely.

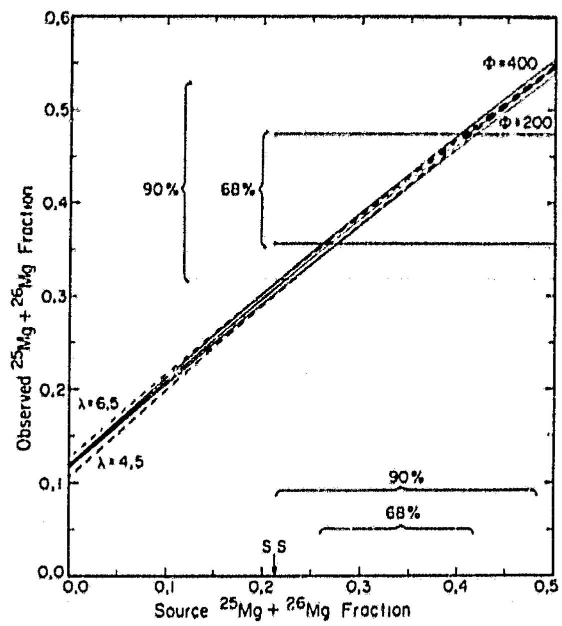

Fig. 3. Calculations of the observed $^{25}Mg + ^{26}Mg$ fraction vs. the source fraction. Solid curves: $\lambda = 5.5$ g/cm², with $\Phi = (300\pm100)$ MeV/nucleon. Dashed curves: $\lambda = 4.5$ and 6.5 g/cm² with $\Phi = 300$ MeV/nucleon. Confidence intervals of 68% and 90% are indicated, as well as the solar system (S.S.) fraction.

From Table 1 and Figure 2 we note that ^{22}Ne, ^{25}Mg and ^{26}Mg appear to be more abundant in the cosmic ray source than in the solar system. For ^{22}Ne we note that the direct isotopic measurements (including Prezler et al. 1975; Garcia-Munoz et al. 1979; Greiner et al. 1979; and this work) all indicate an excess of ^{22}Ne, while there is disagreement among the indirect measurements (Fisher et al. 1976; Dwyer 1978; Simpson et al. 1977). For the direct measurements shown in Figure 2, the mean observed ^{22}Ne fraction is $0.33 \pm .02$, corresponding to a source fraction of $0.27 \pm .03$, and a $^{22}Ne/^{20}Ne$ source ratio ~ 3 times the solar system value of 0.12.

For Mg, the derived $^{25}Mg + ^{26}Mg$ source fraction of $0.33^{+.09}_{-.07}$ (Figure 3) corresponds to a $(^{25}Mg + ^{26}Mg)/^{24}Mg$ source ratio that is $1.8^{+0.8}_{-0.5}$ times the solar system value of 0.27. From a maximum likelihood analysis we find only a 5% probability that the cosmic ray Mg source composition is identical to that of the solar system. For ^{29}Si and ^{30}Si our observations are statistically limited and do not rule out possible enhancements of these nuclei in the source.

4. Discussion. Because the individual isotopes of Ne, Mg and Si differ in mass by ≤ 10%, mass dependent acceleration is unlikely to be significant, and isotopic anomalies in the derived source composition more likely reflect the composition of the material from which cosmic rays are accelerated. Garcia-Munoz et al. (1979) argued that the interstellar medium (ISM) could not be the dominant component of cosmic ray source material, since the expected change in the $^{22}Ne/^{20}Ne$ ratio in the ISM since the birth of the solar system is ≤ 50%. However, there are a wide variety of neon components observed in the solar system (see, e.g., Podosek 1978) and it is conceivable that the solar system neon-A component is not representative of the ISM ~ 4.5 x 10^9 years ago. We therefore conclude only that the solar system neon-A and cosmic ray source compositions are different, independent of their origin.

Several mechanisms of nucleosynthesis are thought to contribute to Ne, Mg and Si isotope production. The major contributions to solar system ^{20}Ne, ^{24,25,26}Mg and ^{29,30}Mg and ^{29,30}Si are thought to come from explosive carbon burning, while ^{21,22}Ne production is the result of He burning, and ^{28}Si is due mainly to explosive oxygen burning. Woosley (1979) suggested two factors that might lead to cosmic ray ^{22}Ne enhancements; we discuss below their implications for the Mg and Si isotopes.

One factor contributing to the ^{22}Ne enhancement might be continuing galactic evolution, since ^{22}Ne and other neutron-rich nuclei are second generation products of nucleosynthesis. Because the cosmic rays (age $\sim 2 \times 10^7$ years) are much younger than the solar system, they may reflect contributions from later stars of higher average metallicity. During helium burning, the larger abundance of metals will result in an increased abundance of ^{22}Ne which in turn is the source of an increased neutron excess η during explosive carbon burning.

The Mg isotopes are particularly sensitive to η, as emphasized by Cassé (1979). Based on Figure 3 of Pardo et al. (1974), our ^{25}Mg + ^{26}Mg excess would result from an increase in η of (30 ± 20)% over the solar system value of $\eta \approx 2 \times 10^{-3}$. On the other hand, a factor of ~ 3 increase in η, as suggested by ^{22}Ne, would lead to ^{25}Mg/^{24}Mg/ and ^{26}Mg/^{24}Mg ratios > 1. It therefore appears unlikely that the Ne and Mg isotope measurements can be explained in a consistent manner in terms of galactic evolution effects alone.

Since ^{20}Ne and ^{22}Ne are produced in different burning processes in different zones of a massive star, Woosley (1979) suggested that a second contributing factor to a non-solar ^{22}Ne/^{20}Ne ratio might be a variation in the relative contribution of these zones, as might be expected if the cosmic rays and the solar system come from stars of different average mass. We note from Couch et al. (1974) and Lamb et al. (1977) that in stars with ~ 8 to ~ 50 $M_\odot$, ^{22}Ne may provide a source of neutrons for a helium-burning s-process with significant yields of ^{25}Mg and ^{26}Mg. A mixture of such helium-burning products with typical carbon-burning yields of ^{20}Ne and ^{24,25,26}Mg (and/or with additional material of solar system composition) could produce the cosmic ray source Ne and Mg composition (Table 1) if the helium-burning yield of ^{25}Mg + ^{26}Mg did not exceed that of ^{22}Ne, a constraint that limits the average mass of the stars involved. We conclude that an enrichment of helium burning products in cosmic rays can enhance both ^{22}Ne/^{20}Ne and (^{25}Mg + ^{26}Mg)/^{24}Mg, as observed, without significantly affecting ^{21}Ne or the silicon isotopes. Observations of other s-process nuclei (see, e.g., Wefel et al. 1977) might test this possibility.

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