1973-15

COSMIC RAY ISOTOPES*

E. C. Stone

California Institute of Technology
Pasadena, California (USA) 91109

November 30, 1973

SRL 73-15

*Rapporteur paper, presented at the 13th International Cosmic Ray Conference, Denver, August 26, 1973

COSMIC RAY ISOTOPES*

E. C. Stone

California Institute of Technology
Pasadena, California (USA) 91109

Since this is the first rapporteur talk on cosmic ray isotopes in thirteen Cosmic Ray Conferences, I will begin by briefly summarizing our interest in isotopic composition as follows:

a) Isotopes, not elements, are the result of various nucleosynthesis processes. Thus, we must know the isotopic composition of cosmic rays in order to adequately exploit the relationship of cosmic rays and stellar processes.

b) Isotopes, not elements, are the result of secondary fragmentation processes, either in cosmic ray source regions or in the interstellar medium. Thus, we must know the isotopic composition in order to completely unravel source composition from secondary composition.

c) Isotopes, not elements, are radioactive. Thus, we must know the isotopic composition in order to take full advantage of various radioactive nuclei as cosmic ray clocks which can be used to determine the age of cosmic rays.

With this short summary, I now turn to a brief review of the results presented at this conference. Since I can't possibly discuss each new measurement, I have chosen the following topics: I) H and He isotopes, II) Be isotopes, III) Al isotopes, IV) Fe isotopes, V) cross sections and model calculations, and VI) instrumental considerations.

I. <u>H and He Isotopes</u>. The relevant results are reported in the following papers:

Session	Paper	Authors	
OG-3A	400	Teegarden, von Rosenvinge, McDonald	- GSFC-1
	159	Hurford, Mewaldt, Stone, Vogt	- CIT
	375	Apparao	- Tata

*Rapporteur paper, presented at the 13th International Cosmic Ray Conference, Denver, August 26, 1973.

Study of the H and He isotopes can provide information on the interstellar spectra of H and ^{4}He, because D and ^{3}He are thought to be secondaries produced almost entirely by galactic cosmic ray ^{1}H and ^{4}He. In particular, the ratio of D/^{4}He is especially sensitive to the primary spectra because low energy D is copiously produced by high energy protons through spallation of interstellar ^{4}He and by the reaction $p+p \rightarrow D+\pi$. Thus, the ratio D/^{4}He at low kinetic energies is really a ratio of a high energy flux (the ^{1}H which produced the D) to a low energy flux (the ^{4}He) and is therefore sensitive to the interstellar spectrum.

At the Hobart Conference, J. P. Meyer (1971) compared extensive calculations of D/^{4}He with data and concluded that the interstellar spectra were close to power laws in total energy. The data available at that time covered the period from ~ 1967 to 1970.

At this conference strikingly different results have been obtained for 1972 by the Caltech and Goddard groups. These new results are shown in *Figure 1*, along with the earlier results summarized by Simpson (1971).

Several points are contained in Figure 1. First, the ratio D/^{4}He was much smaller in 1972 than in previous years. This reduced ratio is partly due to a factor of three reduction in the D flux compared to 1967 and partly due to an enhanced ^{4}He flux which is larger than that observed at the last solar minimum.

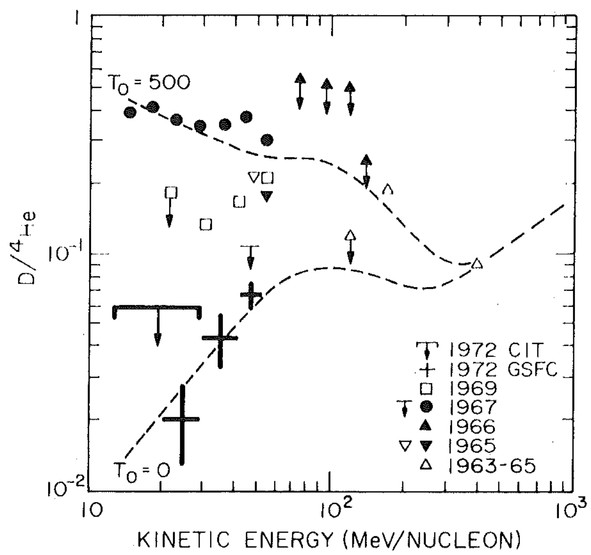

Fig. 1. *The deuterium to ^{4}He ratio. The new 1972 results are compared with previously summarized results and calculations.*

The second key point is that we expect adiabatic deceleration to reduce the energy dependence of the ratio below ~ 200 MeV/nucleon (see, for example, Biswas and Ramadurai, paper 406). Adiabatic deceleration occurs because as the galactic particles penetrate into 1 AU they are diffusing through the expanding interplanetary medium, which produces a "cooling" effect similar to the cooling of a gas in an expanding box. Thus, the 10 to 30 MeV/nucleon particles at 1 AU would all have had higher energies ($\geq$ 100 MeV/nucleon) outside the modulation region and the ratio D/^{4}He below 100 MeV/nucleon should be very similar to that at ~ 200 to 500 MeV/nucleon.

Figure 1 includes the interstellar ratios calculated by Meyer (1971) for power laws of the form $(T+T_o)^{-2.6}$ for the primary ^1H and ^4He spectra, where T is kinetic energy and T_o=0 and 500 MeV. The predicted ratio is ~ 0.1 in the 200 MeV/nucleon region for both assumed power laws. Thus, adiabatic deceleration should have resulted in a similar ratio of ~ 0.1 at lower energies, which is in serious disagreement with the 1972 observations.

One possible explanation is that the propagation of <50 MeV/nucleon particles is not dominated by adiabatic deceleration, but that some fraction of both low energy D and ^4He are gaining access without large energy losses at times near solar minimum. Should this be the case, then the energy dependence of the ratio at 1 AU might directly reflect the unmodulated energy dependence. As shown in Figure 1, there is a striking similarity between the calculated interstellar ratio for the kinetic energy power law case (T_o=0) and the observations at 1 AU.

Another possibility is that either the interstellar D or ^4He spectra is much different than assumed in the model calculations. Perhaps a significant enhancement in the low-energy interstellar ^4He could, even with adiabatic deceleration, produce a noticeable increase in ^4He at 1 AU without a corresponding increase in the production of D.

The proper interpretation of these very recent results may be quite different once the appropriate calculations have been made. There is, however, a strong possibility that our understanding of solar modulation may be significantly modified and that we may obtain important information on the interstellar spectra of low energy H and ^4He.

To close off this subject, I want to mention that Apparao reported an upper limit of D/He< 0.6 above 16.8 GV. In the revised version of the paper, the author points out that the proton background seriously limited the results. An improvement of a factor of 5 to 10 in sensitivity would be of considerable interest, since the D/He ratio at higher energies depends on the proton pathlength in the interstellar medium.

II. Be Isotopes. The relevant results are reported in the following papers:

Session	Paper	Authors	
OG-3A	156	Garcia-Munoz, Mason, Simpson	(Chicago)
	329	Enge, Fukui, Beaujean	(Kiel)

The primary interest here, of course, is in the ^{10}Be isotope, which has a radioactive halflife of ~ 1.5 x 10^6 y and thus is an appropriate cosmic ray clock. However, ^{10}Be is difficult to separate from ^{9}Be, and fluxes of only ^{7}Be and ^{9}Be were resolved by the Chicago group. The Kiel group gave a status report of their investigation which is not yet complete.

The Chicago results for Be are shown in *Figure 2*, which illustrates the mass resolution obtained. Note that the separation of ^{7}Be and ^{9}Be is similar to that of ^{3}He and ^{4}He. There is however, no statistically significant indication of a ^{10}Be peak, and the authors emphasize only that they have clearly separated ^{7}Be and ^{9}Be. The authors do report 3 events in the ^{10}Be region in excess of that expected from ^{9}Be contamination and background.

The Chicago results are

$$\frac{^{7}Be}{Be} = 0.50 \pm 0.07$$

$$\frac{^{9}Be}{Be} = 0.41 \pm 0.10$$

$$\frac{^{10}Be}{Be} = 0.09 \pm 0.10$$

which are consistent with galactic cosmic ray propagation calculations. Because of the large uncertainty of the ^{10}Be flux, no statement can be made about cosmic ray lifetime.

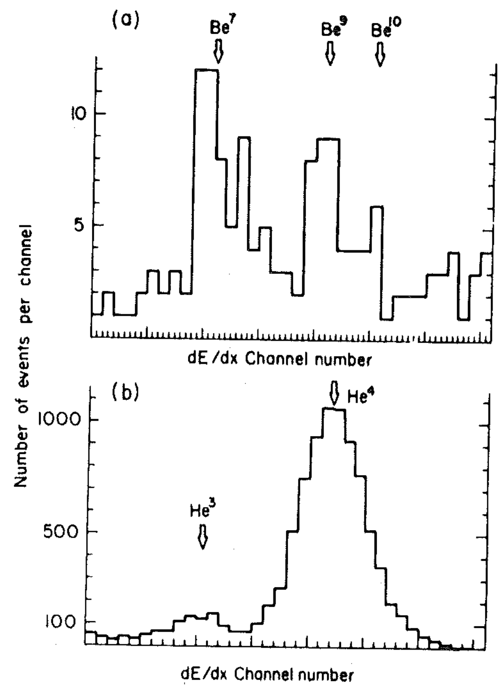

Fig. 2. *The observed mass distributions for Be and He reported by the Chicago group.*

Although not reported at this conference, I do feel that it is appropriate to mention recent results by Webber, Lezniak, Kish, Damle (1973) obtained with a balloon borne instrument. Their results show separation of ^{9}Be and ^{10}Be and they report 7 ^{10}Be nuclei out of 100 Be nuclei observed at 2.9 g/cm^2 atmospheric depth. When adjusted for equal energy intervals and for solar modulation effects, they calculate that they should have observed 18±3 ^{10}Be nuclei if none had decayed. Thus, they conclude that the mean lifetime T_{cr} of cosmic rays is

$$T_{cr} = 3.4^{+3.4}_{-1.3} \times 10^6 \text{ y}$$

This is probably the first indication that we will indeed be able to use ^{10}Be as a clock with further improvements in statistical accuracy, fragmentation parameters, and instrumentation. It is especially important to accumulate at least ~ 100 ^{10}Be nuclei with a given instrument so that any residual instrumental pecularities or background can be quantified and eliminated.

III. Al Isotopes. The relevant papers are the following:

Session	Paper	Authors	
OG-3A	305	Beaujean, Enge	(Kiel)
	043	Webber, Lezniak, Kish	(UNH)

Another possible cosmic ray clock is ^{26}Al, which has a halflife of ~ 7×10^5 y. Since secondary ^{26}Al is the result of the interaction of heavier primaries (e.g., Fe, Ca, Si), while ^{10}Be is produced mainly by lighter primaries (C,O), comparison of these two clocks might indicate whether or not the residence time for the two groups of primaries is the same.

The Kiel group described their work with plastic track detectors which may ultimately yield a mass resolution of σ ~ 0.3 amu. Presently the resolution is ~ 1 amu and no comment is possible on the ^{26}Al abundance.

The UNH group reported results on the isotopic abundances of a broad range of elements. For Al they report

$$\frac{^{25}Al+^{26}Al}{^{27}Al} = \frac{2}{9}$$

where the numbers in the ratio correspond to the observed number of events. They calculate that secondary production would yield at ratio of $^{26}Al/^{27}Al \simeq 0.35$. The observed ratio would be smaller due to either the decay of ^{26}Al or the presence of ^{27}Al in the source. Thus the observed ratio is suggestive of the presence of ^{26}Al, but the uncertainties in the data are presently too large to support any conclusion about the decay of ^{26}Al. The observed mass distribution for Al is included in Figure 3 in the next section.

IV. Fe Isotopes. The relevant papers are:

Session	Paper	Authors	
OG-3A	172	Maehl, Israel, Klarmann	(WU)
	043	Webber, Lezniak, Kish	(UNH)

The isotopic composition of Fe and other heavy elements can provide important information on the nucleosynthesis associated with cosmic ray source regions. The relative abundances of ^{54}Fe and ^{56}Fe are extremely sensitive to such details of the source region as temperature, density, and neutron excess (see, e.g., Reames, 1970, and Arnett et al., 1971). In addition, the production of ^{58}Fe may require source regions different from those producing ^{54}Fe and ^{56}Fe (Truran, 1972). Thus, the isotopic composition of Fe and other heavy elements is of great interest.

The two measurements of Fe isotopes reported at this conference involve quite different techniques. The WU group used the geomagnetic cutoff technique described by Lund, Rasmussen, and Peters (1971) at the Hobart Conference. This method is based on the comparison of the ratio of the flux above a geomagnetic cutoff to the flux above a given velocity for one element to the ratio for a second element. Since the ratio for a given element depends on the spectrum and on the average A/Z for that element, the ratios for two different elements will differ only to the extent that either the spectra or the average A/Z for the two are different. Using this technique, the WU group reports that the average atomic weight for Fe is

$$\bar{A} = 54.6 \pm 0.5$$

The UNH group used an entirely new technique which is based on simultaneous measurements of the Čerenkov radiation (Č) and the total energy (E) for each incident particle. This technique yields high mass resolution over a restricted energy interval just above the threshold of the Čerenkov radiator. An example of the observed mass distributions is shown in *Figure 3* for a number of elements including Al and Fe. Note that the mass distribution at Fe is rather broad. The authors have grouped the observed events as follows:

$^{53+54}$Fe	:	15
$^{55+56+57}$Fe	:	23
$^{58+59+60}$Fe	:	16

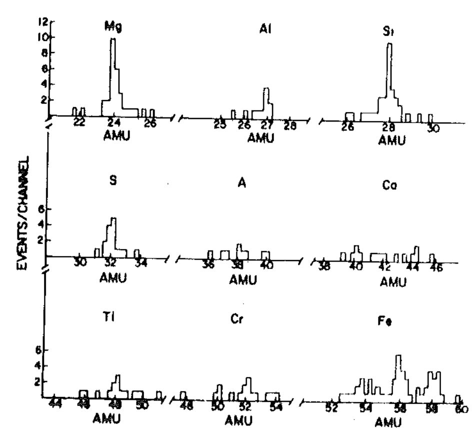

Fig. 3. *The observed mass distributions reported by the New Hampshire group.*

There is no doubt that this Fe distribution and the WU measurement of the mean atomic weight are inconsistent. In discussions during and after the sessions, this discrepancy was not resolved, although there were comments about the statistical weight of the observations and about the background in the relatively thick UNH total-energy detector due to nuclear interactions.* The interest in these results certainly warrants additional analysis and a continuing improvement of these and other techniques.

I should mention that both of these groups also reported results for other nuclei with $10 \leq Z \leq 26$.

V. Cross Sections and Model Calculations. The relevant papers can be grouped as follows:

Session	Paper	Authors
OG-10	444	Jung, Suren, Sakamoto, Jacquot, Kaiser, Schmitt
OG-11	406	Biswas, Ramadurai
OG-3A	225	Tsao, Shapiro, Silberberg
OG-3A	-	Damle, Webber, Kish
OG-10	252	Raisbeck, Perron, Toussaint, Yiou
OG-10	253	Raisbeck, Yiou
	251	Yiou, Raisbeck, Perron, Fontes
OG-10	325	Silberberg, Tsao
	198	Ayres, Schmitt, Merker, Shen
OG-10	482	Cassé

The papers in the first group contain calculations of the expected interstellar abundances of D and ^{3}He. Jung et al. use their recent studies of p,α inelastic processes to calculate the interstellar spectra, which they modulate using the force-field approximation so that comparison can be made with data obtained at 1 AU. Biswas and Ramadurai do a similar calculation, but assume a unique source spectrum which they refer to as the Fermi spectrum. These authors use a numerical solution of the full modulation equation in order to compare with data at 1 AU. It will be interesting to compare in detail these and other calculations with each other and with the new D results discussed above.

The second group of papers contain calculations of the secondary production of the heavier isotopes. Tsao et al. have continued their calculations of abundances and now present results for essentially all of the isotopes from Li through Ni.

---

*For later comments on this discrepancy, see the Post-Conference Comments at the end of this paper.

Figure 4 illustrates some of their results compared to universal abundances. Such results depend on many assumptions, many of which can be tested by the comparison of such detailed calculated abundances with isotope data.

The paper by Damle et al. contains calculations of a more restricted set of isotopes, specifically those of Al, K, Cr, and Mn. These isotopes include ^{26}Al, ^{53}Mn, and ^{54}Mn which may be useful cosmic ray clocks. The two calculations are in qualitative agreement on which isotopes should dominate each element. However, the actual fractional abundances of isotopes of a given element are different in the two calculations, with an rms difference of ~ 0.06. At present, cosmic ray measurements are subject to larger uncertainities, but this situation could change dramatically in the next two years.

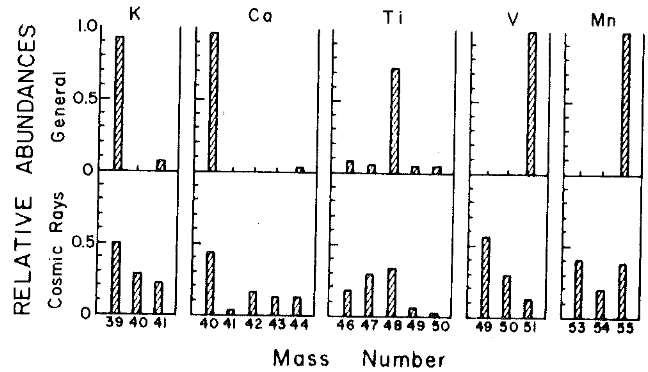

Fig. 4. *An example of the calculated cosmic ray isotope abundances compared with universal abundances (Tsao, et al.).*

The paper by Raisbeck et al. concentrates on the importance of electron capture isotopes in cosmic ray studies. The authors discuss the general aspects of the problem and the need for specific data such as electron attachment and loss cross sections at high energies. They also present a calculation of the fraction of ^{49}V surviving as a function of energy. A substantial energy dependence is predicted in the 100 to 500 MeV/nucleon interval.

The third group of papers by the Orsay group contains some new results and a summary of their current program for measuring the relevant nuclear cross sections. Such experimental results will become increasingly important in the next few years as the quality and quantity of cosmic ray isotope data improve.

In the absence of a complete set of measured cross sections,we will have to rely upon calculations. The fourth group of papers includes results of two types of Monte Carlo calculations which may provide more accurate predictions for some reaction cross sections. At present, it seems that the Monte Carlo calculations are not sufficiently more accurate than the semi-empirical calculations to warrant the much greater computation time. However, continued development of the Monte Carlo technique may results in significant improvements.

In the last group I have included Cassé's calculation of the halflife of ^{56}Ni against β^+ decay. Normally, ^{56}Ni decay is dominated by electron capture, so there is no laboratory data. Cassé calculates that the β^+ decay halflife is ~ 2 x 10^5 y. Thus, if some of the ^{56}Ni thought to be present in the outer layers of a supernovae can be directly accelerated to high energies, it might be observable in cosmic rays at energies high enough so that the time-dilated halflife is comparable with the age of the source.

VI. Instrumental Considerations. In addition to some of the above observational papers, the following papers from the techniques sessions are relevant:

Session	Paper	Author	
TI-4	435	Verma, Herzo	(LSU)
	042	Webber, Lezniak, Kish	(UNH)
	346	Fisher, Ormes, Hagen	(GSFC-2)
	481	Cassé et al.	(SACLAY/DSRI)
	490	Linney et al.	
	714	Valot et al.	

Verma and Herzo describe a new instrument based on the dE/dx-Range-Energy technique using a spark chamber for determining the particle path. The instrument was flown in summer of 1973 and is expected to have a mass resolution of σ ~ 0.5 amu for the isotopes of H through Be.

Webber et al. provide further details of their new Čerenkov - total energy (Č-E) technique which I have already discussed. Presently the charge resolution varies from σ ~ 0.4 to ~ 0.8 amu, depending on Z. The authors feel a substantial improvement is possible.

Fischer et al. described a new instrument combining both multiple dE/dx-Range-Energy and Č-E techniques. The instrument was flown in 1973 and is expected to yield a mass resolution of σ ~ 0.4 amu for low-Z nuclei and ~ 0.7 amu for Fe.

Cassé et al. present details of a new Čerenkov-Range-Čerenkov (Č-R-Č) technique which has been calibrated at the Bevatron. Mass resolution from the calibrations was σ ~ 0.35 to 0.6 amu for N and C. The authors expect that the resolution can be further improved.

Linney et al. describe the new Čerenkov radiators with refractive indices in the range from $1.05 \leq n \leq 1.2$. The radiators, which are made of compressed silica powder, were calibrated at the Bevatron. Such low index radiators are a key design element in future isotope studies at high energies. Additional calibration details for powder counters as well as for more conventional glass and liquid Čerenkov radiators are discussed in Valot et al.

In order to summarize the current status of the measuring techniques for isotope studies, I thought it would be interesting to plot the mass resolution achieved or predicted for various techniques as a function of Z, the charge of the cosmic ray nucleus. *Figure 5* contains such a summary for "present" and "future" results. The "present" resolution

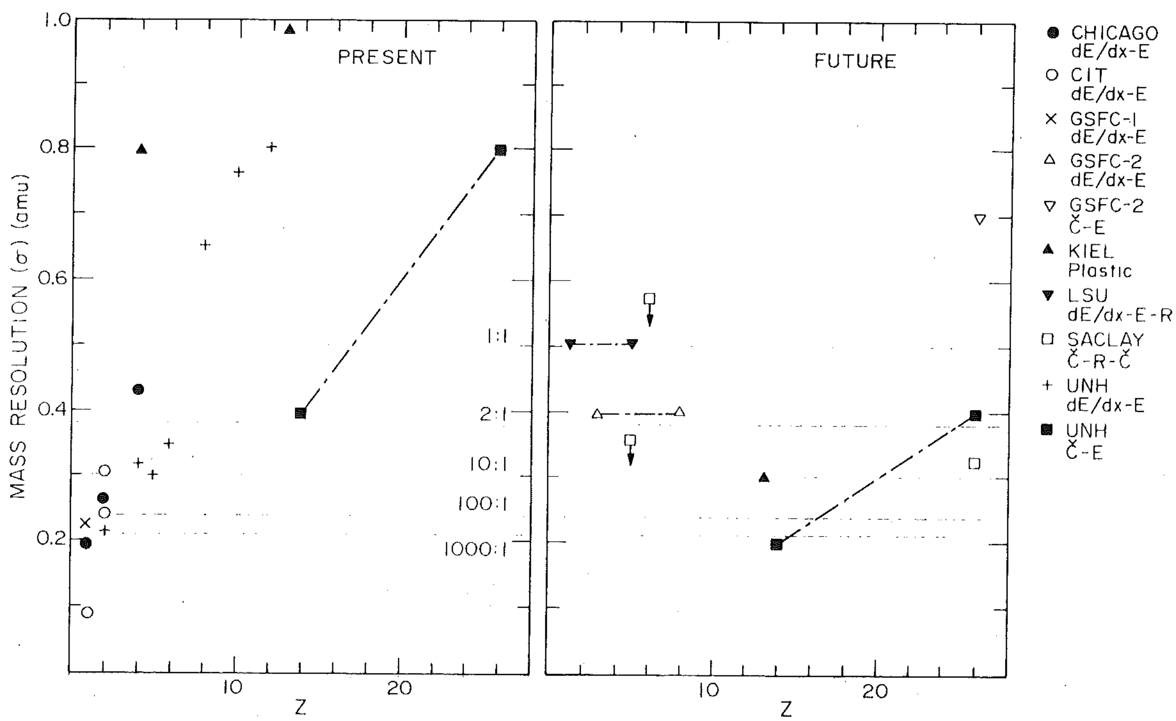

Fig. 5. *A summary of the mass resolution (σ) reported for various elements (Z) compared with the resolution required to separate adjacent isotopes (Δm = 1) with various relative abundances. The "present" resolution values are based on cosmic ray data, while the "future" resolution values are based on calibrations and calculations.*

results are based on measurements of cosmic ray isotopes as reported in the various papers which I have discussed in previous sections. The "future" resolution results are based on calculations or calibrations described in the instrumentation papers discussed earlier and not on actual flight data. I have not attempted to include other "future" techniques which were not reported at this conference.

Figure 5 also includes 5 resolution levels with labels of 1:1, 2:1, 10:1, 100:1, and 1000:1. These levels are indicative of the resolution required to separate adjacent isotopes ($\Delta m=1$) with relative abundances of 1:1, 2:1, etc. For isotopes separated by 2 amu, the levels would be a factor of 2 higher. Thus, separation of two even isotopes with relative abundances of 10:1 requires a resolution of $\sigma \lesssim 0.6$ amu, provided that the intermediate odd isotope is non-existent.

Examination of *Figure 5* indicates that satellite instruments are now capable of separating isotopes of only the lightest elements (at relatively low energies). The major improvements in the immediate future seem to be in balloon instruments for heavier nuclei at higher energies where resolution of individual isotopes may become a reality. So, the next two years should be exciting. Of course, there has been progress in the last two years. At Hobart there was controversy about the elemental abundance of Fe. At this conference we have progressed to a controversy about the isotopic abundance of Fe. Hopefully, there will be even more stimulating results at the next conference.

POST-CONFERENCE COMMENTS. Since the conference I have given further thought to the use of the geomagnetic cutoff to determine the average A/Z of different elements. The actual formulation used by the WU group (paper 172) is based on the assumption that the integral momentum-per-nucleon spectrum for element i can be represented by $J_{ip} = \alpha_i \, p^{\gamma_i}$ over the interval between the cutoff and a fixed momentum/nucleon p. It is not possible, of course, to determine the correct power law in this interval with a balloon flight at a 3 GV cutoff because of the unknown penumbral and east-west effects. Therefore, the WU group used the spectral index in a slightly higher energy interval, i.e., the ~ 830 to ~ 1270 MeV/nucleon interval, as an estimate for the index in the 700 to 860 MeV/nucleon interval near cutoff. It should be noted that if the absolute value of the actual γ_{Fe} in the ~ 700 to ~ 860 MeV/nucleon interval was smaller than in the measured energy interval, then the derived value of A/Z would be too small.

A qualitative evaluation of this possibility can be obtained by examining the differential kinetic energy spectra shown in *Figure 4* of paper 171. It appears that the shape of the Fe and the $22 \leq Z \leq 24$ spectra are changing rather rapidly in the 800 to 1300 MeV/nucleon interval, making it difficult to accurately extrapolate into the crucial 700 to 860 MeV/nucleon interval. Since the trend in *Figure 4* is toward a flatter Fe spectrum at lower energies, i.e., a smaller absolute value for γ_{Fe}, the mean A/Z for Fe may be larger than reported. Because of this uncertainty, the WU group has subsequently withdrawn their result for the mean mass of Fe.

The cutoff technique relies upon accurate knowledge of the spectra in the cutoff region, suggesting that essentially simultaneous flights at low and high latitudes will be necessary. In this way, the mean A/Z can be determined at the higher cutoff using the accurately measured spectra obtained at the lower cutoff to specify the γ_i in the critical energy interval associated with the higher cutoff region.

ACKNOWLEDGEMENTS. I appreciate comments by R. A. Mewaldt on this manuscript.

PRE-CONFERENCE REFERENCES

Arnett, W. D., J. W. Truran, and S. E. Woosley, 1971, Ap.J., 165, 87.

Lund, N., I. L. Rasmussen, and B. Peters, 1971, Conf. Papers 12th Int. Cosmic Ray Conf. Hobart, 1, 130.

Meyer, J. P., 1971, Conf. Papers 12th Int. Cosmic Ray Conf. Hobart, 7, 2565.

Reames, D. V., 1970, NASA/GSFC Report X-662-70-423.

Simpson, J. A., 1971, Conf. Papers 12th Int. Cosmic Ray Conf. Hobart, rapporteur papers, 324.

Truran, J. W., 1972, Ap.J., 177, 435.

Webber, W. R., J. A. Lezniak, J. Kish, and S. V. Damle, 1973, The relative abundance of the isotopes of Li, Be and B and the age of cosmic rays, preprint, Univ. New Hampshire.