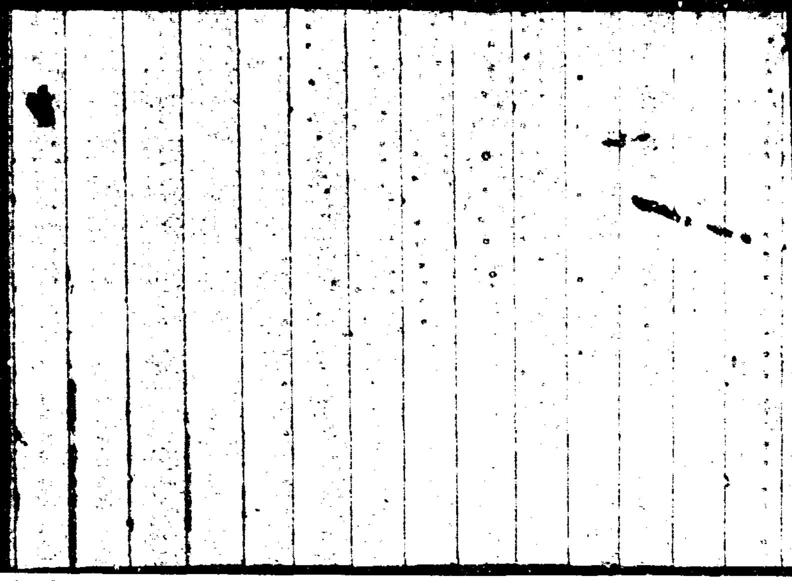

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The Charge and Energy Spectra of Heavy Cosmic Ray Nuclei

by

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Abstract

A charged particle detector array flown in a high altitude balloon has detected and measured some 3×10^4 cosmic ray nuclei with $Z \geqslant 12$. The charge specrtum at the top of the atmosphere for nuclei with $E > 650$ MeV/n and the energy spectrum for $650 \leqslant E < 1800$ MeV/n are reported and compared with previously published results. The charge spectrum at the 'source' of cosmic rays is deduced from these data and compared with a recent compilation of 'galactic' abundances.

Introduction:

A determination of the charge and energy spectra of the heavier nuclei ($Z \geq 12$) in the primary cosmic radiation can provide information on several important questions. These include the general problem of the propagation of cosmic ray particles through the interstellar medium, as well as the nature of the possible source region. Since it has become apparent that the chemical composition of the matter that is accelerated to high energies is not radically different from the general run of astrophysical samples of matter, it has become necessary to try and look for small differences. Clearly any distinctive characteristics of high energy matter could lead to a better understanding of the origin of cosmic rays. It is therefore necessary that on these nuclei we attempt to make measurements that have good statistical weight and charge resolution. This paper describes the results from one such observation, using a large but lightweight detector that could be employed to make measurements of much greater duration.

Experimental Details

A large area, lightweight detector of heavy cosmic ray nuclei was flown on a high altitude research balloon for 11 hours at a mean altitude of 2.6 mb from Fort Churchill, Manitoba, on August 8, 1974. This detector consisted of four active elements, two scintillation counters and two Cerenkov counters arranged in the configuration shown in Fig. 1. In all four elements the light pulses produced by the radiators were emitted into a diffusion box and then collected by photomultiplier tubes (PMT's). In the Cerenkov elements the outputs of six PMT's evenly spaced around the perimeter were summed and analyzed by quasi-logramithic 2048 channel pulse height analyzers (PHA's). In the scintillation elements the outputs of four PMT's, three around the perimeter and one mounted in the center, were separately analyzed by similar PHA's. This last feature permitted us, by using the relative pulse heights in each PHA, to locate the impact position of each cosmic ray nucleus on both of the 1.22 m diameter scintillators to within a standard deviation of 4.5 cms, (Scarlett, 1977).

In this detector the geometry was defined by the two Cerenkov radiators, giving a corrected geometry factor of $0.410 \pm 0.007\ m^2sr$ and thus, with a total live time of 3.432×10^4 secs, an exposure factor for the flight of $3.91 \pm 0.07\ m^2sr$ hrs. The total weight of the complete detector, which was flown unpressurized and covered only by an aluminized mylar solar blanket, was 225 kg, and as a consequence the atmospheric corrections were kept to a minimum. Some 3×10^4 nuclei with $Z \geqslant 12$ were detected at a float altitude that decreased steadily from 1.5 mb to 3.8 mb.

The flight data were processed by determining the trajectory of each particle and, after making corrections for the path length through the detectors and for non-uniformities in light collection and thickness, constructing plots of the outputs of the scintillation counters versus those of the Cerenkov counters. This procedure, which is rather standard, but tedious, is described in detail in Scarlett (1977). One unique feature, the position location, will also be described in detail elsewhere.

The uncertainty in charge and energy determination depends on fluctuations in the energy deposited in the scintillators and the number of photoelectrons in the Cerenkov detectors as well as on the accuracy of the corrections for thickness, uniformity variations, and for path length. The thickness and uniformity corrections were accurate to an average of 0.5 % and the path length correction to 1.3 %. A detailed analysis of the factors affecting the charge and energy resolution is given in Scarlett (1977).

Experimental Results

a) Charge Spectra

The resulting charge distribution is shown in Fig. 2, which plots the mean charge of nuclei having $E \geqslant 550$ MeV/n in the detector as determined from the values calculated separately in the top and bottom pairs of counters. Examination of this figure shows that the FWHM of each of the charge peaks at $Z = 12$, 14, and 16 is one unit of charge, which suggests a standard deviation, σ of 0.42 charge units, inadequate to resolve individual neighboring elements on a one-to-one basis, Waddington (1977), but adequate to determine the features of the main charge peaks and to allow statistical separation of the elements in samples of sufficient weight. Fig. 2 is based on 20,525 nuclei that satisfied all the requirements imposed to remove interactions and other sources of degradation. It is therefore possible to unfold the distribution, using a multiple linear regression technique, Bevington (1969). This technique assumes gaussian distributions with fixed mean and standarded deviations and derives the relative abundances best fitting the experimental distribution. The assumption of gaussian peaks is generally reasonable though due to the relativistic rise in the scintillators there is a small tail on the high side. Hence, high energy nuclei from an abundant element can contaminate the next higher peak. This problem is particularly evident in the contamination of the cobalt and nickel peaks by high energy iron. The results are given in Table 1, where the errors shown include those for both statistical and goodness of fit.

These results have to be corrected for several effects in order to determine the abundances at the top of the atmosphere. Among these corrections are those for interactions in the detector, and in the overlying atmosphere, as well as corrections for the selection criteria used to qualify events for inclusion in Fig. 2 and for the energy window used. The interaction corrections have been made using the cross-sections for interactions of heavy nuclei in air of Meyer et al (1977 and private communication), together with a propagation program due to Hagen (1976 and private communication). The resulting intensities at the top of the atmosphere are also shown in Table 1, with errors that include an estimate of the errors in the various corrections. It may be noted that the largest corrections are in general for effects in the detector, which are relatively well-known, while the atmospheric corrections, which are less well determined, are significantly less, due to the small amount of residual atmosphere.

However, it is also clear that even for a relatively thin detector such as this, the corrections for effects in the detector are large and any uncertainties in the nuclear parameters will lead to similar large uncertainties in the calculated intensities. Partly for this reason, and partly because of the intensity variations due to solar modulation, few of the recent experiments in this field have attempted even to quote absolute intensities but instead discuss only the relative abundances, where the effects of these corrections will be reduced, although not eliminated.

The abundances that we find of the elements relative to iron are compared in Fig. 3 with those of a number of other experiments. The agreement is reasonable in view of the differing corrections applied and the varied energy ranges covered in the experiments. There is some indication that the magnitude of the odd-even effect we observe is somewhat less than that reported by the majority of other experiments. This suggests that we have not been entirely successful in unfolding the distributions. It can be noted that for several of the elements the quoted errors lie well outside those to be expected for a unique value. Whether this is due to energy dependent variations, or to experimental optimism, is not clear at present. Examination of Fig. 3 also suggests that the total relative number of nuclei is not the same in all experiments, but that there are quite wide divergences in total relative numbers. This is illustrated in Fig. 4, which shows the integrated relative number of nuclei as a function of decreasing charge for $Z \leqslant 25$, for several of the experiments shown in Fig. 3. While some of these differences could presumably be a consequence of the differing magnitude of the corrections applied, the energy independence of the corrections implies that at least some of the differences are energy dependent. It should be noted that our data are the only ones that are for all energies above the lower limit. In every other case an energy range is specified, with both an upper and a lower limit. Hence our sample must include proportionately more high energy nuclei than do any of the others. Our lower rate of growth in Fig. 4 can be explained by assuming that the iron nuclei have a flatter energy spectrum than do the lighter nuclei. This interpretation is supported by the observations of Julliot et al (1975), No. 5 in Fig. 3, which have the highest energy limit of any of the other experiments and also show a low rate of growth.

Such a difference between the energy spectra of the iron nuclei and those lighter is in agreement with an extrapolation of our own results at moderate energies, to be discussed shortly, and with those reported by other groups. The uneven quality of the data makes it unreasonable to attempt an analysis of these energy spectra differences, although they appear to be consistent with what would be expected.

In view of the previous discussion we have no reason to doubt the general validity of our <u>absolute</u> intensity values, which we consider to be the best available at this time, although the relative intensities are no better than others reported. It can be noted that if we sum the intensities for $Z \geqslant 20$ nuclei with $E > 650$ MeV/amu we obtain a value of 0.865 ± 0.018 nuclei/m^2.sr.sec, which is in good agreement with the value of 0.891 ± 0.05 obtained by Freier and Waddington (1968) for VH-nuclei above the same energy limit and at a time of similar low solar modulation. If we assume that each element has the same mean mass number A as solar system matter then we can calculate the total nucleon intensity brought into the earth's atmosphere by each element. The total intensity of $E > 650$ MeV nucleons brought in by nuclei with $Z \geqslant 12$ is thus 94.8 ± 1.9

nucleons/m^2.sr.sec.

b) Energy Spectra

The energy spectrum for a particular charge can be derived over a limited energy range from the Cerenkov signals. In this case we find that, up to the highest energy considered, errors of less than 1% are introduced by neglecting the convolution corrections described by Lezniak (1975) and assuming instead that we are using a perfect detector having a δ-function redistribution function. In order to calculate energy spectra we initially selected a set of energy windows at the top of the atmosphere. For each charge a corresponding set of windows was then calculated at the detector in the center of C_{top} for a particle at the secant θ averaged incident angle of 20°, with the telescope at the mean depth of 2.58 g/cm^2. The number of particles in each window was then determined. Fig. 5(a) shows the resulting differential energy spectra for iron nuclei, iron secondaries ($21 \leq Z \leq 25$), calcium nuclei, light iron secondaries ($17 \leq Z \leq 19$) and sulphur nuclei. Similarly, the integral spectra are shown on Fig. 5(b).

Although most of the differential spectra look as though they could be represented by power laws, this is only true over the very limited energy ranges shown. Examination of all the data, including the integral intensities for E > 1800 MeV/nucleon, show that none of the spectra can be truly represented by a simple power law in any of the usual motion parameters, total or kinetic energy, or rigidity.

However, it is clear from Fig. 5(a) that the iron nuclei have a flatter differential spectra in the energy region $650 \leq E \leq 1800$ MeV/n than do the other elements, even though the integral spectra are rather similar.

Fig. 6 shows the abundance ratio of iron secondaries to primary iron as a function of energy, together with data from other groups. Also shown is the prediction of a propagation calculation, Maehl et al (1977), which assumes no appreciable abundance of iron secondary nuclei at the source, an energy independent leakage path length of 5 g/cm^2, and energy dependent cross-sections from the semi-empirical formula of Silberberg and Tsao (1973a, 1973b).

However, recent measurements by Raisbeck and Yiou (1975, 1977 and private communication) of some of the cross-sections for the fragmentation of iron on protons and helium nuclei indicate that only a small fraction of the energy variation of the iron secondary to iron ratio can be accounted for by energy dependent fragmentation. Thus it seems more likely that an energy dependent leakage path length is required to explain the data, even at these relatively low energies.

c) Source Abundances

The abundances measured at the top of the atmosphere have been propagated to the source using a leaky box model with $\lambda_e = 5\ g/cm^2$. The propagation program, written by F. Hagen (1976) uses a matrix technique originally described by Cowsik and Wilson (1973). The results are shown in Table 2 along with those of Garcis-Munoz et al (1977), and Fisher et al (1976). Also shown are the 'galactic abundances' of Meyer and Reeves (1977).

The results of this work, which are in substantial agreement with those of Garcia-Munoz et al (1977), show generally good agreement with the galactic abundances, but with a few distinct differences. The most striking disagreements are the S/Fe and Ar/Fe ratios. Cosmic ray sulphur is diminished by a factor of 2 to 4 while Ar appears to be absent in the source. On the other hand, the abundances of Si and Ca are in good agreement with the galactic values. It must be pointed out that the galactic abundances of Ar and S are not well known, (Casse and Meyer, 1977).

There have been two types of explanations for the source composition of cosmic rays, either nucleosynthesis including mixtures with the interstellar medium (eg., Hainbach et al, 1976) or preferential acceleration which is dependent on some atomic property such as the first ionization potential (Haynes, 1973; Kristiansson, 1974; Casse et al, 1975). The former attempts to find a particular nucleosynthesis process which explains the cosmic ray source abundances. The latter notes that there appears to be a correlation between the ratios of the cosmic ray to galactic source abundances and the first ionization potential (or other atomic parameter.)

Shapiro and Silberberg (1977) and Schramm and Arnett (1977) have recently concluded that neither explanation can completely explain the cosmic ray abundances and that a hybrid of the two approaches is probably required. Casse and Meyer (1977) have reviewed the Si, S, Ar, and Ca abundances both in the galaxy and in the cosmic ray sources and have concluded that the cosmic ray source abundances cannot be explained by explosive Si burning, the process proposed to be the principle source of the four elements. They also conclude that no one S abundance in the galaxy is consistent with present views on both nucleosysthesis and production of the cosmic ray source composition.

It appears that at this time there is neither enough detailed information about the nucleosysthesis processes nor about the cosmic ray source composition to reach a definite conclusion. The low Ar and S abundances do lend support to the theories that preferential acceleration is at least in part responsible for the cosmic ray source abundances. Isotopic composition measurements of the heavy nuclei should place enough constraints on both the nucleosysthesis mechanisms and on the cosmic ray source composition to greatly improve our knowledge of both.

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Z	Fit to Z-spectrum (particles)	Detector Correction	Atmosphere Correction	Energy Correction	Intensity nuclei. m^{-2}. sr^{-1}. sec^{-1}.	Intensity nucleons. m^{-2} sr^{-1}. sec^{-1}.
12	4375±70	1.422	1.105	1.306	0.667±0.062	16.22±1.51
13	1322±48	1.450	1.106	1.192	0.180±0.011	4.86±0.30
14	4948±73	1.491	1.132	1.038	0.616±0.016	17.31±0.45
15	49[illegible]±3[illegible]	1.511	1.101	0.980	0.058±0.004	1.80±0.12
16	117[illegible]	1.551	1.101	0.963	0.137±0.005	4.40±0.16
17	3[illegible]	1.574	1.056	0.963	0.035±0.003	1.24±0.11
18	4[illegible]±25	1.623	1.001	0.964	0.0465±0.003	1.69±0.11
19	[illegible]4±26	1.623	1.050	0.972	0.0405±0.003	1.58±0.12
20	742±33	1.636	1.099	0.981	0.093±0.004	3.73±0.16
21	266±25	1.716	1.112	0.982	0.035±0.005	1.58±0.22
22	493±29	1.740	1.007	0.982	0.060±0.004	2.88±0.19
23	251±25	1.752	0.977	0.986	0.030±0.003	1.53±0.15
24	544±32	1.785	1.061	0.990	0.0725±0.004	3.77±0.21
25	354±39	1.809	1.078	0.995	0.049±0.005	2.70±0.28
26	3128±65	1.818	1.187	1.000	0.480±0.014	26.84±0.78
27	83±28	1.883	1.192	1.005	0.013±0.004	0.77±0.24
28	194±18	1.889	1.207	1.010	0.032±0.003	1.88±0.18

Table 1.

Table 1.

Table 2.

Relative abundances of the cosmic ray nuclei at the source.

Z	This work:	Galactic abundances Meyer & Reeves (1977)	Garcia-Munoz et al (1977)	Fisher et al (1976)
12	92±16	123±4	---	153
13	22±4	9.8±0.4	---	17
14	96±7	116±4	125±15	127
15	7±2	1.1±0.4	<2	5.3
16	16±3	45.4±16.3	16±3	20
17	2.4±1.2	0.4±0.23	<2	---
18	<2	5.8±3.5	<3	4.67
19	2±2	0.4±0.1	<3	---
20	9±3	7.6±0.5	14±5	11.3
21	4±1	0	<2	---
22	<3	0	<4	---
23	<2	0	<3	---
24	<3	1.5±0.2	<3	2.0
25	<3	1.0±0.3	<2	1.3
26	100	100±9	100	100
27	---	0.2±0.05	<0.4	-
28	7.3±1	5.4±0.6	5±2	---

FIGURE CAPTIONS:

1. Schematic arrangement of the detectors.

2. Histogram of $(Z_{top} + Z_{bottom})/2$ for particles with T>550 MeV/n. Note that since these data are not corrected the relative abundances are not those at the top of the atmosphere.

3. Abundances relative to iron obtained in this experiment and compared with results reported by: 1. Meyer and Minegawa (1977), 2. Tueller et al (1977), 3. Garcia-Munoz et al (1977), 4. Lund et al (1975), 5. Juillot et al (1975), 6. Benegas et al (1975), 7. Webber et al (1972), 8. Fisher et al (1976).

4. Integrated number of nuclei relative to an iron abundance of 100 as a function of decreasing charge. References are the same as in Fig. 3.

5. (a) Differential energy apectra as a function of kinetic energy.

   (b) Integral energy spectra as a function of kinetic energy.

   -- Lines are drawn through the various experimental points to guide the eye, not represent a mathematical fit.

6. Ratio of iron secondaries to iron nuclei as a function of kinetic energy.

REFERENCES

Benegas J., M.H. Israel, J. Klarmann and R.C. Maehl (1975) Proc. of Munich Cosmic Ray Conf. 1, 263.

Bevington, P.R. (1969) Data Reduction and Error Analysis for the Physical Sciences, McGraw Hill, p. 164.

Casse M., P. Goret and C.J. Cesarsky (1975) Proc. of Munich Cosmic Ray Conf. 2, 20.

Casse M., and J.P. Meyer (1977) Proc. of Bulgarian Cosmic Ray Conf 2, 131.

Cowsik, R., and L.W. Wilson (1973) Proc. of Denver Cosmic Ray Conf. 1, 500.

Fisher A.J., F.A. Hagen, R.C. Maehl, J.F. Ormes and J.F. Arens (1976) Astrophys. J. 205, 938.

Freier, P.S. and C.J. Waddington (1968) Phys. Rev. 175, 1641.

Garcia-Munoz, M., G.M. Mason and J.A. Simpson (1977) Proc. of Bulgarian Cosmic Ray Conf. 1, 224.

Hagen, F.A. (1976) GSFC Report X-660-76-54.

Hainbach K. L., J.C. Clayton, W.D. Arnett, and S.E. Woosley (1974) Astrophys. J. 193, 157.

Hainbach K.L., E.B. Norman, and D.N. Schramm (1976) Astrophys. J. 203, 245.

Haynes, O., (1973) Astronomy and Astrophysics 24, 435.

Julliot, C., L. Koch and N. Petron (1975) Proc. of Munich Cosmic Ray Conf. 12, 4118.

Kristiansson K. (1974) Astrophysics and Space Sci. 30, 417.

Lund, N., I.L. Rasmussen and B. Peters (1975) Proc. of Munich Cosmic Ray Conf. 1, 263.

Maehl, R.C., J.F. Ormes, A.J. Fisher and F.A. Hagen (1977) Astrophysics and Space Sci. 47, 163.

Meyer, J.P., M. Casse and P. Goret (1977) Proc. of Bulgarian Cosmic Ray Conf. 2, 213.

Meyer, P. and G. Minagawa (1977) Proc. of Bulgarian Cosmic Ray Conf. 1, 249.

References, continued.

Raisbeck, G.M. and F. Yiou (1975) Proc. of Munich Cosmic Ray Conf., 2, 502.

Raisbeck, G.M. and F. Yiou (1977) Proc. of Bulgarian Cosmic Ray Conf., 2, 63.

Scarlett, W.R. (1977) PhD Thesis, University of Minnesota.

Schramm, D.N. and W.D. Arnett (1977) Proc. of Bulgarian Cosmic Ray Conf., 2, 10.

Shapiro, M.M., and R. Silberberg (1977) Proc. of Bulgarian Cosmic Ray Conf., 2, 20.

Silberberg, R. and C.H. Tsao (1973a) Ap. J. Suppl. 25, 315.

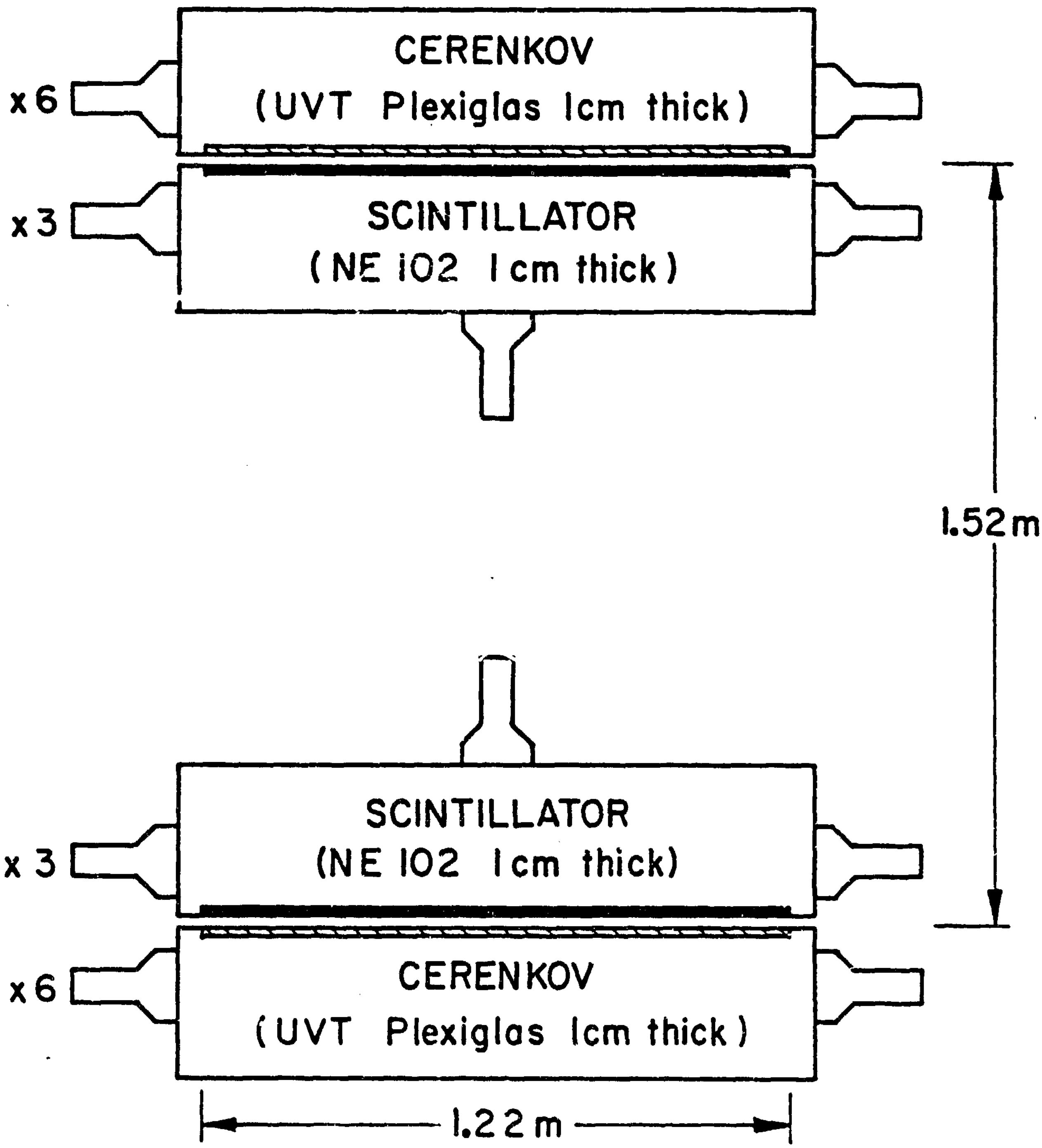
Silberberg, R. and C.H. Tsao (1973b) Ap. J. Suppl. 25, 335.

Tueller, J., P. Love, J.W. Epstein, M.H. Israel and J. Klarmann (1977) Proc. of Bulgarian Cosmic Ray Conf. 1, 254.

Waddington, C.J. (1977) Proc. of Bulgarian Cosmic Ray Conf., Rapporteur Paper.

Webber, W.R., S.V. Damle and J. Kish (1972) Astrophysics and Space Sci., 15, 245.

Webber, W.R., J.A. Lezniak, J.C. Kish and S.V. Damle (1973) Nature, Phy. Sci., 241, 96.



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(NE 102 I cm thick)
x3
1.52m
SCINTILLATOR
(NE 102 I cm thick)
x3
CERENKOV
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x6
1.22m

Figure 1.

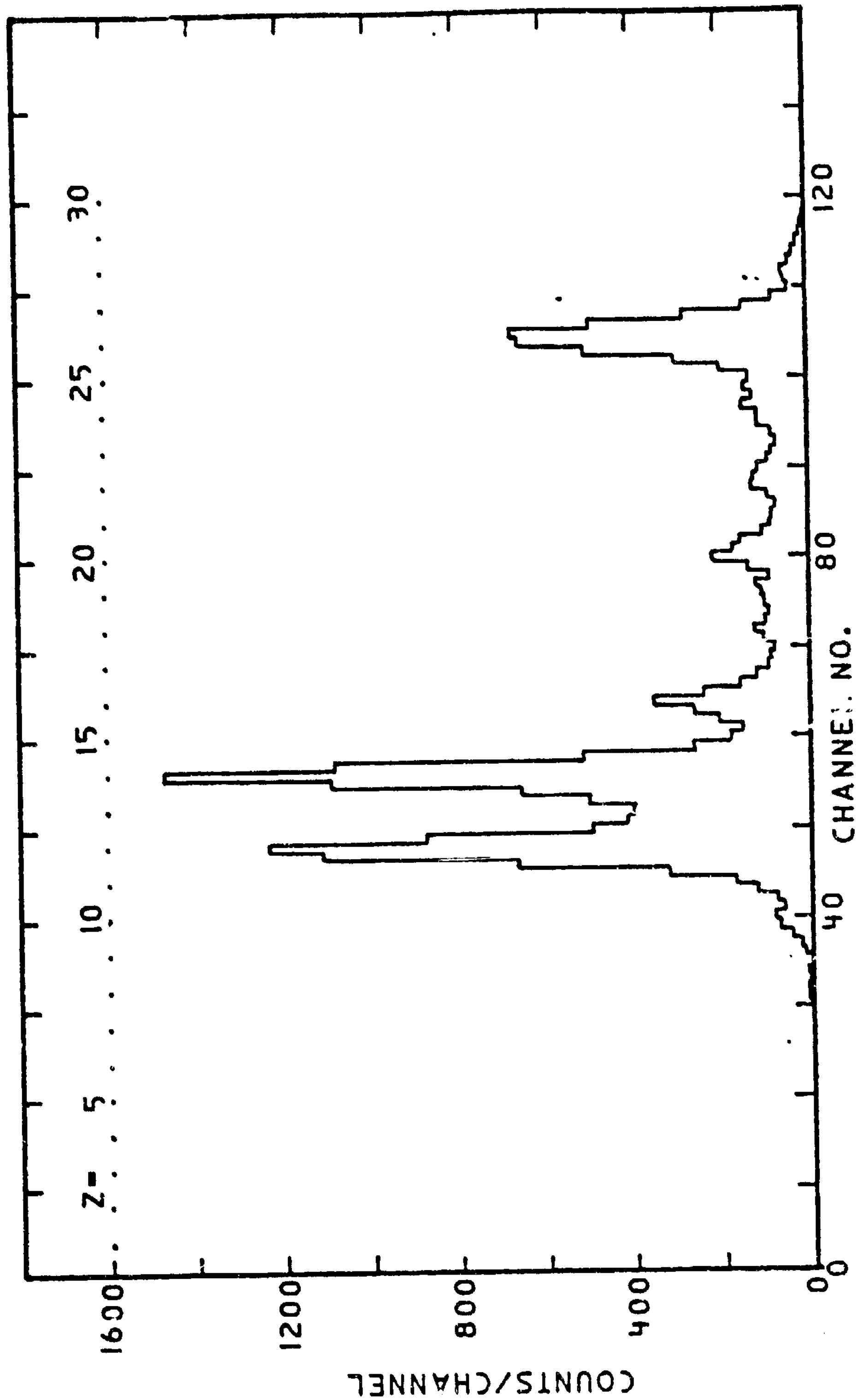

Figure 2.

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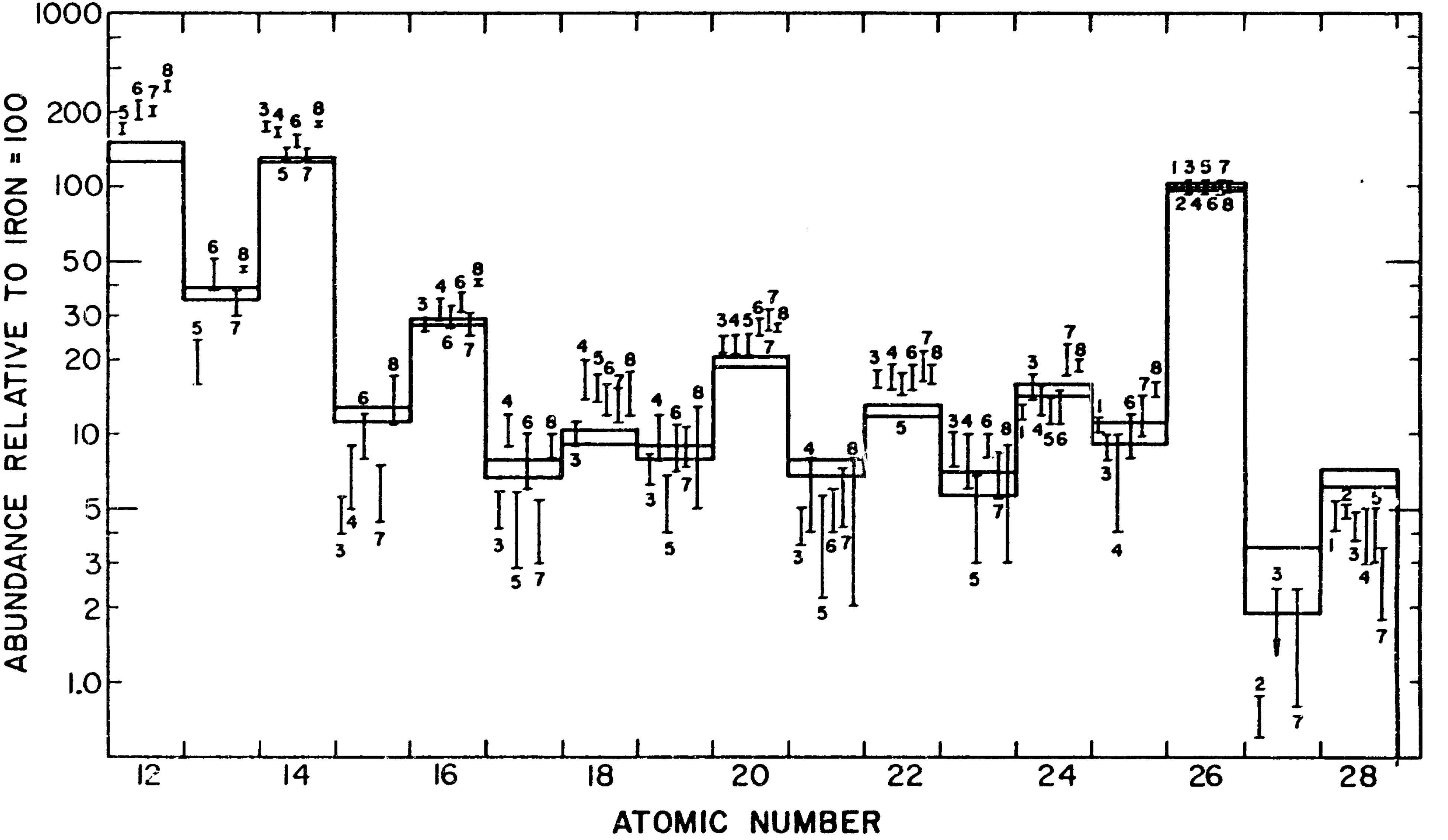
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Figure 3.

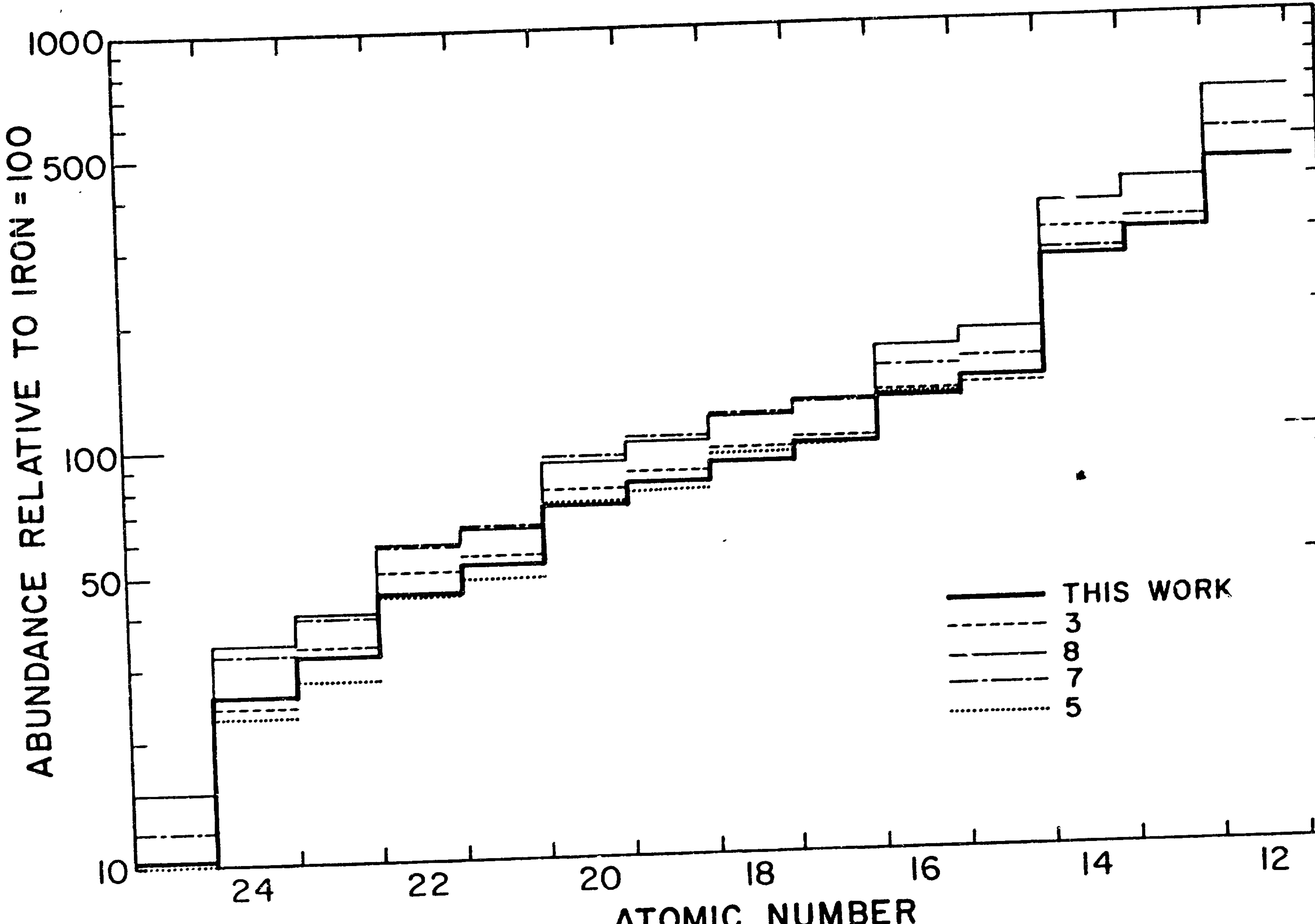
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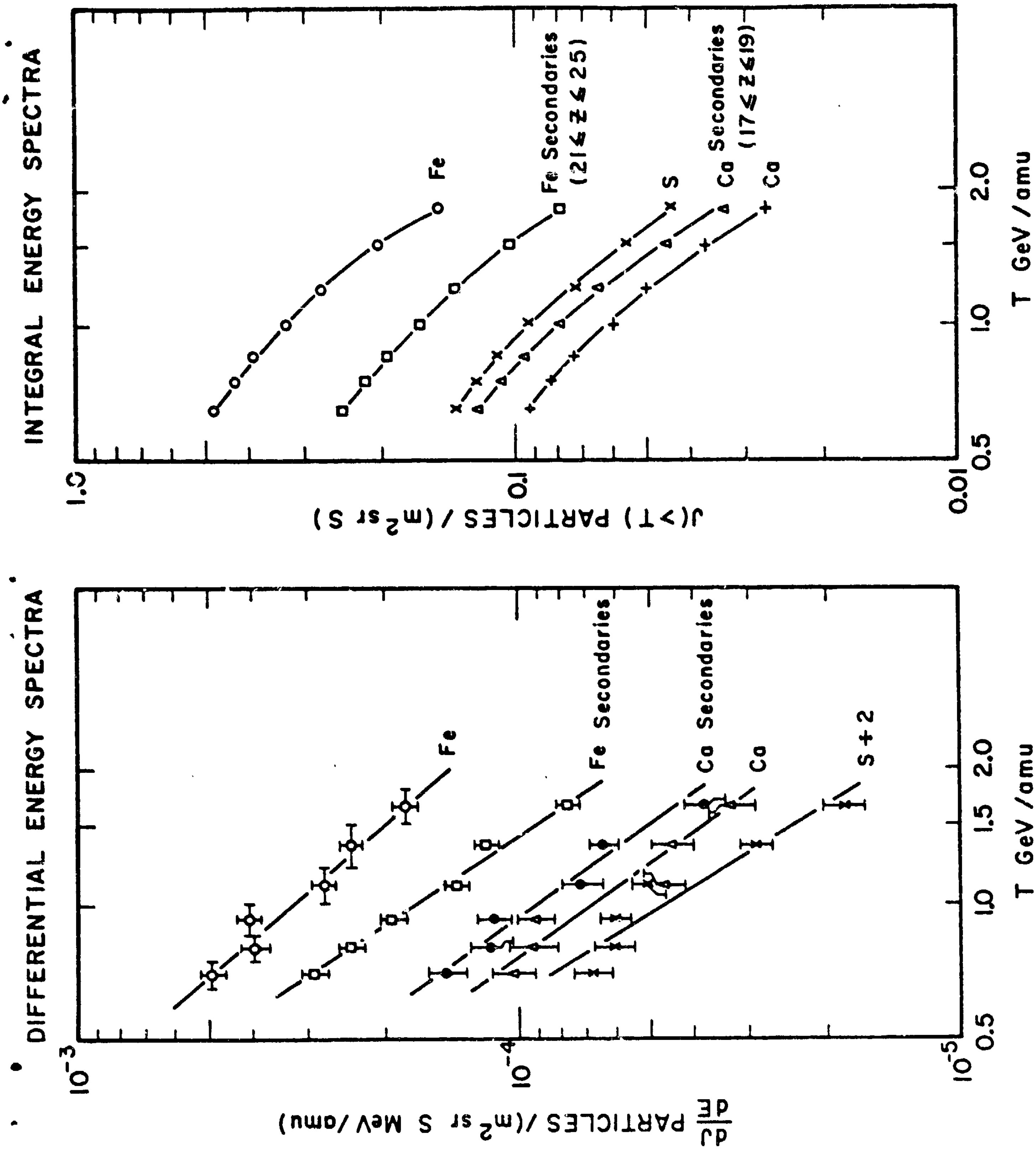
Figure 4.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J(>T) PARTICLES / (m² sr S)
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DIFFERENTIAL ENERGY SPECTRA
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Figure 5.

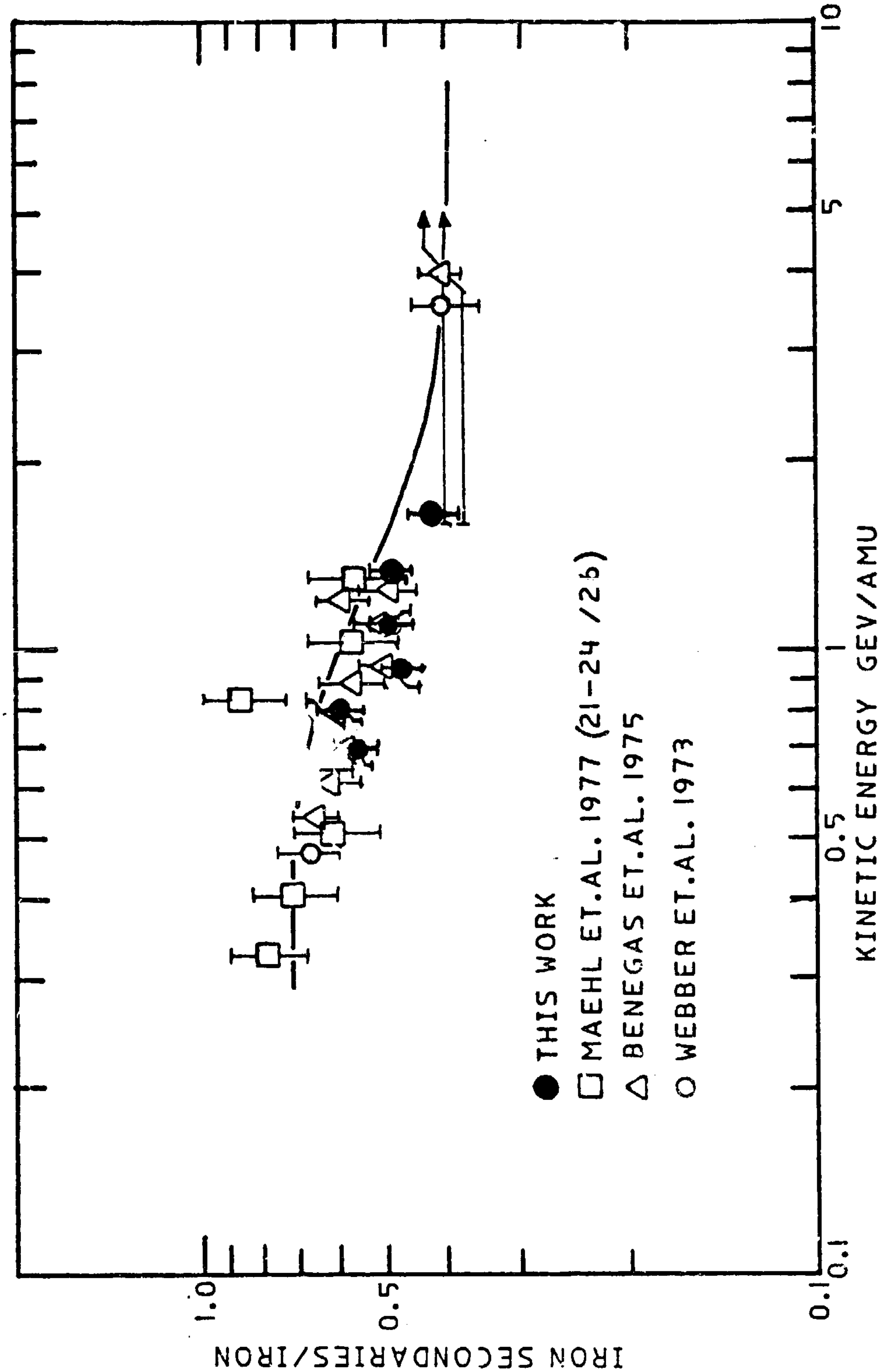
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Figure 6.