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A MEASUREMENT IN NUCLEAR EMULSION OF THE ISOTOPIC
ABUNDANCE OF COSMIC RAY NITROGEN AND OXYGEN

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The particle masses are determined from photometric measurements of track widths.

The standard deviation in the mass determination is calculated to 0.45 AMU for nitrogen and 0.50 AMU for oxygen. Special checks of possible errors originating from emulsion disturbances are made.

The mass scale of nitrogen is calibrated with an accuracy of ± 0.1 AMU. The calibration is made by using the concept of restricted energy loss. The following results are obtained of the isotope quotients extrapolated to the top of the atmosphere

$$\begin{aligned} {}^{14}\text{C}/\text{O} &= 0.05 \pm 0.03 & {}^{18}\text{O}/\text{O} &= 0.08 \pm 0.03 \\ {}^{15}\text{N}/\text{N} &= 0.33 \pm 0.09. \end{aligned}$$

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This report discusses a measurement of the isotopic composition of the cosmic ray nitrogen and oxygen. The detector is a stack of nuclear emulsions which was exposed in a balloon flight in northern Canada. The particle energy is 220-450 MeV/n.

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The standard deviation in the mass determination is calculated to 0.46 AMU for nitrogen and 0.50 AMU for oxygen. Special checks of possible errors originating from emulsion disturbances are made.

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Introduction

The isotopic composition of the elements in the primary cosmic radiation gives important information concerning the origin of the radiation. The quotient $^{15}\text{N}/\text{N}$ in the radiation gives information concerning the amount of nitrogen in the cosmic ray source and is therefore of major importance in the search for the source and the mechanism which selects the cosmic ray particles (Arnett and Schramm, 1973; Koslovsky and Ramaty, 1973; Kristiansson 1971, 1974; Cassé and Goret, 1973).

According to a calculation by Meneguzzi et al. (1971), this quotient is ~ 0.6 , if no nitrogen exists in the source, and ~ 0.4 , if nitrogen is present in the same amounts as in the solar system. For oxygen, the dominant isotope in the galaxy is with great certainty ^{16}O . However, it cannot be completely excluded that the heavier oxygen isotopes are also present in some possible sources and can contribute to the radiation, at least in certain energy intervals (Hoyle and Clayton, 1974). The isotopic compo-

sition of oxygen is therefore also well worth studying. In the radiation, small amounts of ^{17}O and ^{18}O are also expected to exist as secondary particles from interactions with interstellar matter. (Tsao et al. 1973).

Measurements of the isotopic composition of nitrogen and oxygen have already been made. The results of these measurements are in many cases accompanied by large statistical errors and the presence of systematical errors cannot always be excluded. Most of the measurements have been made with various kinds of counter telescopes. In this report a measurement in a stack of nuclear emulsions is discussed. This type of detector probably gives small systematical errors but the number of particles registered is usually comparatively small. The present report mainly describes the technique of the measurement.

The detector was exposed in a high altitude balloon flight from northern Canada. The energy of the particles accepted for the measurement was 220-450 MeV/nucleon at the top of the atmosphere. The particles were identified by photometric track width measurements. The photometer and the technique of measurement are described in section I. In section II, the various corrections applied on the track widths are discussed. In the next section, the principle of the mass determination is described, and in sections IV and V the expected mass resolution is calculated, and checks of possible emulsion disturbances are made. The calibration of the mass scale of nitrogen is treated in section VI and finally the results are given in the last section.

I. The measurements

1. The detector.

The particle detector, used in this investigation, is a stack of 61 Ilford G5 emulsions, each one having the dimensions $10 \times 10 \times 0.06 \text{ cm}^3$.

The stack was exposed during an 8 h balloon flight from Fort Churchill, Canada, in June 1970, at a depth of $2.6 - 3.4 \text{ g/cm}^2$. The packing material covering the stack was 0.5 g/cm^2 in the mean.

The emulsions were developed according to the temperature cycle method with the dry hot stage at 20°C . The blob density for relativistic singly-charged particles was 18 blobs/100 μm . The whole stack was area-scanned for stopping particles with $Z \geq 3$.

2. The photometer.

The determination of the mass of a particle is based on the relation between track width and residual range. For the measurements of track widths a nuclear track photometer was used the construction of which is similar to that described by Jönsson et al. (1970). The photometer construction is shown in Fig. 1. The basic unit of the photometer is a Leitz microscope, the eye-piece of which has been replaced by an optical system with a slit arrangement and a photomultiplier. The image of a track section is focused in plane A in a central slit, with the dimensions corresponding to $33 \times 4 \text{ } (\mu\text{m})^2$ in the object plane. Two background slits are positioned $3 \text{ } \mu\text{m}$ outside the central slit, each having the dimensions $33 \times 3 \text{ } (\mu\text{m})^2$. The slit system and the focused track can be viewed by means of the Leitz Mz tube via a glass prism with a semi-transparent mirror. A new image of the

track section and the slits is formed in plane B. A movable diaphragm allows light to pass to a photomultiplier either through the central slit or through the background slits. An interference filter in front of the photomultiplier transmits light in the 540-550 nm wavelength region.

The photometric track width W is defined by the expression

$$W = \frac{c U_2 - U_1}{c U_2},$$

where U_1 is the photometer signal of the central slit with the track in position, and U_2 is the corresponding signal of the background slits. The factor c compensates for the difference in the areas of the central slit and the background slits.

The photometer signal is automatically digitalized and punched on paper tape. The electronic system is described by Andersson et al. (1973).

3. Track selection and width measurements.

All tracks found in the scanning that had a dip angle less than 37° were preliminary measured with a photometer in order to determine the charge of the particles. The charge resolution was 0.25 charge units in the interval carbon-oxygen.

Particles with $Z = 6, 7$ and 8 were selected.

The particle tracks had to fulfil two further conditions in order to be accepted for the track width measurements on which the mass determination is based.

1. The tracks must have a dip angle relative to the horizontal plane, which is less than 33° in the unprocessed emul-

sion.

2. At least 9 mm of the track in the range interval $1 < R < 12$ mm must be more than 8 mm from the edge of the emulsion

All nitrogen and oxygen tracks fulfilling the selection criteria were measured whereas only a fraction of the carbon tracks was included in the investigation. The number of measured tracks was about 180. The track widths were measured along the tracks from the stopping point to 12 mm residual range. Each measurement covered $33 \frac{1}{3}$ μm , which means that the total number of width values of a track is 360.

The reproducibility of the photometer was checked by measuring a calibration track regularly during the period of measuring. By using two different operators to measure many of the tracks a further check of the reproducibility was achieved. The result of the calibration track measurements and the double measurements show that the time drift over the 150 days of measuring was 1.0%, which was corrected for. The difference between the operators was 0.3%.

In addition to the time drift there exists a statistical fluctuation of about 0.3% in the measured mean value of W of a track. This uncertainty in the measured W -level can be caused both by fluctuations in the photometer response and by effects caused by the operator. For tracks which were measured twice or more, the mean value of the measurements was used.

In about 5% of the double measurements, extreme differences occurred between the two measurements. Such differences may be caused by air bubbles in the immersion oil. The existence of such accidents makes it important to measure all tracks twice. The nitrogen tracks were therefore measured at least twice. As

the oxygen tracks were mainly intended to be used for calibration purposes, about half of those tracks were measured only once. However, all oxygen tracks with extreme values of the mass were controlled by a second measurement. Therefore, it is improbable that the mass spectrum of oxygen is affected by accidents in the measurement.

4. Excluded measurements.

Of the normally 360 W-measurements in a track some measurements were excluded for different reasons.

All measurements nearer to an edge than 8 mm were excluded since both distortion and processing may affect the tracks near the edges.

During the track width measurements the operator excluded such measurements as seemed to be disturbed. The disturbances were in most cases caused by crossing tracks and dark spots. The number of disturbed measurements was 1%.

Measurements that are very close to the glass or the surface can be disturbed by emulsion effects. Therefore, all measurements closer to the glass or surface than 10 μm in the processed emulsion were excluded. The fraction of such measurements was 7%.

II. The corrections

1. A general outline.

The width of a track in nuclear emulsion depends on the charge, mass and the residual range of the particle. The track width, W , measured with the photometer, is also affected by the properties of the photometer and by effects in the emulsion plates. These effects have to be eliminated before the track width can be used for the identification of isotopes. The following corrections were applied to the widths:

1. The depth correction.
2. The plate normalization.
3. The dip correction.
4. The correction for edge effects.

The corrections were calculated from all the measured track widths of C, N and O tracks, normalized with width-range relations for each charge.

The correction procedure has been discussed several times in different papers. The correction procedure for isotope measurements in the same stack and with the same photometer has been described in detail by Bjarle, Herrström (1976). Therefore, in this paper the corrections will be very briefly treated.

2. The depth correction.

When the light beam passes through the emulsion, part of the light is scattered. This effect makes the track look grey deep in the emulsion and W will be the smaller the deeper the measurement is made in the emulsion. Furthermore, there may exist a depth gradient in the degree of development of the emulsion, which also affects W . Earlier investigations have shown that

the dependence of track width on the depth $W(D)$ can be described by $1/W(D) = (1+b \cdot D) \times \frac{1}{W(0)}$, where D is the depth and b is a depth correction factor (Behrnetz et al., 1973). If the depth is normalized to 0 at the surface and 100 at the glass, the value of b is 0.0025 as an average. For different plates the value of b varies between 0.0016 and 0.0033. The statistical uncertainty in b is about 0.0002 for most plates.

3. Plate normalization.

The mean value of the W -values corrected for the depth are not the same for all plates. This may be due to a slight difference in the degree of development of the plates. The effect can be corrected by normalizing all plates, by a plate factor, to a mean level for the whole emulsion stack.

The number of measurements on which the plate factors are based varies between 280 and 1400 in the different plates. As the standard deviation in the W -measurements is 11%, the statistical errors in the plate factors will be 0.6 - 0.3% with a mean value of 0.4%.

As the track structure changes with the residual range there exists a possibility of a range dependence in the plate factors. A sensitive test of this effect is to compare plate factors obtained from the measurements in the range interval 1-12 mm with plate factors obtained from the last millimeter, which has quite a different track structure. In Fig. 2 the correlation is shown between plate factors from $R=0-1$ mm with factors from $R = 1-12$ mm. The slope of a fitted line is 1.04 ± 0.07 , which indicates that no large range dependence exists where tracks of carbon, nitrogen and oxygen are involved.

Plate factors were calculated separately, for the oxygen tracks and for the nitrogen and carbon tracks. The relation between these two sets of plate factors is shown in Fig. 3. The slope of a fitted line is 1.03 ± 0.07 .

The results thus show that the same factors can be used for carbon, nitrogen and oxygen in the whole range interval.

4. Correction for dip effects.

The dip angle, α , of a track is the angle between the emulsion plane and the particle trajectory in the unprocessed emulsion. The measured value of W is dependent on α in a complex manner.

The dip correction was made by subtracting from the W -values a small term $F(\alpha)$ which is almost independent of the range R . In Fig. 4, $F(\alpha)$ is shown for oxygen and carbon. The oxygen points are mean values of W from the range interval 1-12 mm. The statistical errors in the points are about 0.0006 W -units, which corresponds to 0.15 AMU in the final mass-spectrum. The curve for carbon is based on tracks from an investigation of carbon isotopes by Bjarle et al. (1976). The curve for nitrogen was not possible to determine with enough accuracy from the small number of nitrogen tracks. The correction for nitrogen was therefore calculated by a linear interpolation between the corrections for carbon and oxygen.

5. Corrections for edge effects.

Measurements made a few millimeters from the edge of the plates are usually disturbed. Consequently all measurements closer to the edges than 8 mm were excluded. Furthermore, it was found that the W -level varied slightly with the distance to the edge, even for larger values than 8 mm. This is shown in Fig. 5 where

normalized W-values are plotted as a function of the distance to the nearest edge. A correction of the W-values was applied according to the curve in the figure.

III. The mass determination

1. Computation of the mass.

The energy loss per unit length $\frac{dE}{dR}$, for a particle, is a function of the velocity βc and the charge number Z . The relation between energy loss and track width measured with the photometer is complex. However, it is here sufficient to use the formal notation

$$W = g_1 \left(\frac{dE}{dR} \right) \quad (1)$$

According to the Bethe formula the energy loss can be described by the relation

$$\frac{dE}{dR} = Z^2 \cdot f_1(\beta c) \quad (2)$$

If the equation is integrated and E is substituted by

$E = Mc^2 \left(\frac{1}{\sqrt{1-\beta^2}} - 1 \right)$, where M is the particle rest mass, the relation can be written

$$R = \frac{M}{Z^2} f_2(\beta c) \quad (3)$$

and

$$v = \beta c = f_2^{-1} \left(\frac{Z^2 \cdot R}{M} \right) \quad (4)$$

Combining eqs. (1) and (2) and (4), the track width can be written as a function of Z , M and the residual range R :

$$W = g(Z^2 \cdot R/M) \quad (5)$$

For particles with the same charge the track width can be reduced to

$$W = f(R/M) \quad (6)$$

This function is the basis for the mass determination from measurements of track widths and residual range.

The experimental relations between W and R were approximated by functions

$$F(R) = \sum_i a_i R^i, \quad (7)$$

where $i = 0, 1/2, 1, 2$ and 3 .

The constants a_i , were determined by a least squares fit to the experimental mean W - R relations.

The function $F(R)$ thus describes the W - R relation for a particle with the mass \bar{M} , which is the mean mass of the measured particles. According to eq. (6) the W - R relation for a particle with mass M can be written

$$F(R) = \sum_i a_i (R \cdot \bar{M}/M)^i \quad (8)$$

The mass of the particle is then calculated by fitting $F(R)$ to the experimental width values of the track, with \bar{M}/M as the free parameter. Thus the calculation gives only mass values relative to the mean mass of the measured particles.

The fit was made by minimizing the sum

$$S = \sum_{n=3}^{40} (F(n) - \bar{W}(n))^2 \cdot N_n \quad (9)$$

n = the residual range in the units of 0.3 mm.

$\bar{W}(n)$ = the mean value of the W -values of the track in the range interval $(n - \frac{1}{2}) \times 0.3$ to $(n + \frac{1}{2}) \times 0.3$ mm.

N_n = the number of accepted measurements upon which the $\bar{W}(n)$ -val is based.

2. The mass spectra.

The mass distributions of the oxygen and nitrogen particles are shown in Fig. 6 and Fig. 7 respectively.

To be accepted in these final mass spectra the tracks had to fulfil three further conditions beyond those mentioned in section I:3.

3. The dip angle must be greater than 4.6° in the unprocessed emulsion.
4. The number of accepted width measurements in the track must be greater than 250.
5. The zenith angle must be less than 70° . This excludes particles that have passed more than $\sim 9 \text{ g/cm}^2$ of air.

Condition 3 implies that all tracks have been measured in at least two plates, thereby reducing the error in the plate normalization.

The mass scale in Fig. 6 is based upon the assumption that the main peak is a ^{16}O -peak. The curve in the Figure is a Gaussian distribution with the expected standard deviation $\sigma = 0.50 \text{ AMU}$. (See section IV). Particles falling outside this distribution are classified as isotopes other than ^{16}O .

Fig. 7 shows the distribution of the masses of the nitrogen nuclei. The position of the mass scale cannot be determined accurately owing to the uncertainty as to which stable and unstable isotopes possibly exist in the mass spectrum. Therefore the mass scale had to be determined by a special method of calibration which is described in section VI. The mass spectra are discussed in more detail in the last section.

IV. The expected mass resolution.

The mass resolution depends both on the properties of the emulsions and on the photometer. The main factors which determine the resolution are:

- i. The separation between the W-R relations of consecutive isotopes.
- ii. The statistical fluctuation of the W-measurements.
- iii. Errors originating from the corrections of W.
- iv. Fluctuations in the response of the photometer.

i. The separation $\Delta W(R)$ between the W-R relations of two isotopes with masses M_1 and M_2 can be approximately written:

$$\Delta W(R) = \left(1 - \frac{M_1}{M_2}\right) \cdot R \cdot \left(-\frac{dW(R)}{dR}\right)$$

The variation of $\Delta W(R)$ with range is thus determined by the product of the range and the gradient of the W-R relation.

The gradient of the W-R relation, $\left(\frac{dW}{dR}\right)$, has its largest value near $R = 1$ mm and decreases then towards 12 mm. The product $R \cdot \left(\frac{dW}{dR}\right)$ is however fairly constant in the whole range interval. $\Delta W(R)$ is shown in Fig. 8a for oxygen with $M_1 = 16$ and $M_2 = 17$. $\Delta W(R)$ is about 1.5% of the mean value of W in $1 \leq R \leq 12$ mm.

- ii. The standard deviation of the W-measurement, σ_W , depends on the fluctuations in the track structure and the background. The dependence of σ_W on the range is shown in Fig. 8b for oxygen.
- iii. The most important statistical errors in the corrections are the errors in the plate factors, which amount to about 0.4%. On an average, a track passes through 6 plates. The error from the plate factors is therefore about 0.16%, or 0.11 AMU. The

errors in the depth correction have only insignificant influence on the mass spectrum. The reason is that the accepted W-values of a track are evenly distributed at different depths in the emulsions. The plate factor will then almost completely eliminate the error in the depth correction. The errors in the correction for the dip and the edge distance are small.

iv. The fluctuation of the photometer response was determined by the double measurements of many of the tracks. The fluctuations may depend on both instrumental effects and on effects caused by the operator. The standard deviation of the fluctuations was 0.3% or 0.2 AMU. For the nitrogen tracks, this value was reduced to 0.14 AMU by taking the mean value of the two measurements.

The expected standard deviation in the mass determination $\sigma_M(\Delta R_i)$, calculated from n_i measurements in a range interval ΔR_i at the residual range R_i , is

$$\sigma_M(\Delta R_i) = \frac{\sigma_W(R_i)}{\Delta W(R_i) \cdot \sqrt{n_i}}$$

The error in the mass determination σ_M , based on measurements in a range interval $1 \leq R_i \leq R$ mm, is given by

$$\left(\frac{1}{\sigma_M}\right)^2 = \sum_1^R \left(\frac{1}{\sigma_M(\Delta R_i)}\right)^2$$

where the summation is made to the range R.

Fig. 9a shows the expected standard error $\sigma_M(\Delta R_i)$ as a function of range for one mm long track segments. The most useful information for mass determination is between 2-4 mm residual range. As the information varies only slightly with range, no rangedependent weights were used in the mass calculation. In Fig. 9b,

the integrated value σ_M is shown as a function of measured track length. The value of σ_M at 12 mm is 0.43 AMU. The fact that 9% of the measurements in a track were excluded will increase the calculated value of σ_M by 4.4%. To this value it is necessary to add the contribution from the effects mentioned in iii and iv above. The following Table 1 shows how the mass resolution changes when the different effects are successively added.

Table 1:

	<u>The σ_M (AMU) at 12 mm</u>	
	<u>oxygen</u>	<u>nitrogen</u>
Calculated value	0.43	0.41
9% excluded measurements	0.45	0.43
Plate factor errors	0.46	0.44
Photometer fluctuations	0.50	0.46

Thus, the analysis of the errors has shown that a mass distribution with a standard deviation amounting to 0.50 AMU for oxygen and 0.46 for nitrogen can be expected. As can be seen from Figure 6, the calculated resolution for oxygen is in good agreement with the width of the main peak in the mass distribution.

V. Checks of disturbances.

The calculation above of σ_M claims that no errors exist apart from the statistical ones described above. The effect of systematic errors may show up as tails in a Gaussian distribution of the masses. Such tails especially influence the estimate of the abundance of the rare isotopes ^{15}O , ^{17}O , and ^{18}O . Therefore, special checks of the measured track widths were made in order to find disturbances that could give rise to tails in the distribution. In these checks, it was especially controlled as to whether there was any difference between tracks classified as ^{16}O and tracks classified as ^{15}O , ^{17}O , and ^{18}O .

1. The distribution of W-values.

In an earlier mass measurement in another emulsion stack it was found that a few percent of the W-values was strongly disturbed (Jönsson et al. 1970). This effect caused tails in the distribution of the W-values and destroyed the mass resolution. By excluding W-values far out in the distribution, the mass resolution was drastically improved.

In this investigation no such effects were found. In Fig. 10, the distribution of ΔW -values is shown both for ^{16}O , and for $^{15}\text{O} + ^{17}\text{O} + ^{18}\text{O}$ -tracks. ΔW is equal to the difference between the measured W-values and the W-R relation. The two histograms are nearly Gaussian distributions, however, with a small skewness towards great ΔW -values.

No large changes occur in the mass values when measurements far out in the distribution are excluded. This can be seen in Fig. 11, which shows a comparison of the mass values calculated both with and without excluding W-measurements outside $\pm 2 \sigma$.

The systematic smaller mass values after the exclusion are an effect of the skewness in the ΔW -distribution.

2. The distribution of the sums S.

When calculating the masses, the sum, here called S, of the squared deviations is minimized. This sum is a measure of the spread of the W-values around the W-R relation. The distribution of S for the oxygen tracks is shown in Fig. 12. The experimental distribution shows a slight excess of great values of S compared with the expected χ^2 -distribution. This may indicate the presence of some extreme W-values in a few tracks. Tracks having mass values less than 15.0 AMU or greater than 17.0 AMU are specially indicated in the Figure. The distribution of the S values for these tracks does not differ significantly from the distribution for ^{16}O -tracks. Therefore, there is no reason to believe that these tracks have been wrongly identified, due to the effect of extreme W-values.

3. The distribution of plate W-levels.

Variations in the sensitivity or in the degree of development in different parts of a plate can cause disturbances which cover a large range interval of a track. This possible effect was investigated by studying the distribution of the W-levels of different tracks in a plate. The W-level of a track in a plate is defined as the mean value of the normalized W-values. The difference between a single track W-level and the mean level of all tracks in the plate was divided by the expected standard error of that difference. The distribution of these normalized differences would have the standard deviation equal to 1 if no large scale disturbances exist in the plate. Fig. 13 shows the

sum of the distributions for all plates. The large histogram is for ^{16}O -tracks, and the small for $^{15}\text{O} + ^{17}\text{O} + ^{18}\text{O}$ -tracks. The standard deviations of the distributions σ_p are given in Table 2.

Table 2

	σ_p
^{16}O -tracks	1.00 ± 0.05
$^{15}\text{O} + ^{17}\text{O} + ^{18}\text{O}$ -tracks	0.96 ± 0.06
Expected value	1.00
1% disturbance in the plates	1.19

If large scale disturbances exist there will be an appreciable increase in σ_p . This is shown in the last line of the Table where σ_p is calculated with the assumption that a 1% disturbance exists. The disturbance was applied to the plate W-levels as a normally distributed disturbance with the standard deviation equal to 1%.

A comparison between the σ_p values in the Table shows that the large scale disturbances inside a plate are very small and exert insignificant influence on the mass values.

4. Mass determination in two range intervals.

Another test of the existence of emulsion irregularities is to compare mass values calculated in different range intervals. The differences between mass values obtained from the range interval 1-6 mm and 6- 2 mm are shown in Fig. 14. The histogram for ^{16}O -tracks follows closely the expected distribution. The $^{15}\text{O} + ^{17}\text{O} + ^{18}\text{O}$ -tracks do not have a significantly broader distribution.

VI. The calibration of the nitrogen mass scale.

The mass scale in Fig. 14 was determined through an interpolation procedure based on the experimental W-R relations for ^{12}C and ^{16}O . The starting point for this interpolation is the fact that the track width can be described by the ionization parameter - restricted energy loss, REL, - and that the W-REL relation is, at the first approximation, independent of the particle charge. (Jensen et al. 1972).

The restricted energy loss for a particle with the charge number Z and the velocity βc is computed from the relation given by Barkas (1963).

$$\text{REL} = \frac{2\pi n Z^2 e^4}{\beta^2 m c^2} \left[\ln \frac{2mc^2 \beta^2 \gamma^2 W_0}{I^2} - \beta^2 - 2 C(\beta) \right] \quad (10)$$

where W_0 is the chosen energy limit for secondary electrons, I is the mean ionization potential of the atoms in the emulsion and $C(\beta)$ is a correction which accounts for the density effect at high velocities and for the shell correction at low velocities. n is the electron density. m, e is the electron mass and charge.

It is reasonable that the value chosen for the parameter W_0 corresponds to the effective maximum range for δ -rays which is covered by the slit in the photometer. The chosen values are $W_0 = 20$ keV and $I = 331$ eV. It should be stressed that the calibration of the nitrogen mass scale is very insensitive to the precise values of W_0 and I .

Fig. 15 shows the relation between track width W and restricted energy loss REL. The curves are based on the fitted W-R relations of tracks which were determined to ^{12}C and ^{16}O in the investigation. The carbon curve corresponds to the residual range

interval $1.3 < R < 7.1$ mm, and the oxygen curve to the interval $2.0 < R < 10.8$ mm. The two curves do not exactly follow each other. This is due to differences in the track structure at the same REL. A special consequence of this is that the number of δ -rays in the back groundslits is different and this also affects the measured W-value.

The relation between W and REL for nitrogen was obtained by a linear interpolation between carbon and oxygen in the interval $730 \text{ MeV/cm} < \text{REL} < 1330 \text{ MeV/cm}$. Outside this interval, it was not possible to get an accurate relation for nitrogen.

In the mass computation, the mass values were calculated relative to the mass \bar{M} , which is the mean mass of the particles included in the W-R relation $F(R)$. Cf. eq. (8) above. To obtain an absolute value of the particle masses, it is therefore necessary to determine the value of \bar{M} .

To determine this mean mass \bar{M} of a group of particles, the relation $W = F(R)$ is first determined. By means of the W-REL relation in Fig. 15, the REL-value is then obtained for a given range R. This REL-value corresponds to a certain β according to formula (10). The mass is finally computed from the relation $R = \frac{M}{z^2} \cdot \lambda(\beta)$, where $\lambda(\beta)$ is the residual range of a proton with the velocity βc . The proton ranges are taken from Barkas (1963).

Fig. 16 shows calculated values of \bar{M} for the 16 particles in Figure 14 which had the lowest mass values and which were supposed to be ^{14}N . The curve in Fig. 16 is derived from the $W = F(R)$ relation whereas the points are based on mean values of W calculated for range intervals of about 1 mm.

The mass \bar{M} seems to vary slightly with the range but the trend

is not significant. \bar{M} is set equal to the mean value 14.07 AMU in the whole range interval $2 \text{ mm} < R < 7.5 \text{ mm}$.

The uncertainty in the mass calibration depends on the error in the calculated W-REL relation for nitrogen and on the uncertainty due to the fact that the calibration is only made for part of the range interval.

The error in the W-REL relation is caused by the statistical errors in the mean W-R relations of the tracks of ^{16}O and of ^{12}C . The error of the W-level in the REL-interval $740 \text{ MeV/cm} < \text{REL} < 1350 \text{ MeV/cm}$ is 0.10% for oxygen and 0.15% for carbon. As a mean value was used for nitrogen, the error in the W-REL relation of nitrogen is 0.09% or 0.07 AMU.

The calculation of the mass \bar{M} is made only for the range interval $2 \text{ mm} < R < 7.5 \text{ mm}$. In the calculations of the relative masses of the nitrogen nuclei, the range interval $1 \text{ mm} < R < 12 \text{ mm}$ has been used. To obtain the absolute mass values for these relative masses, a \bar{M} for the whole interval is needed. It has been assumed that \bar{M} for the whole range interval is equal to 14.07 AMU. This implies that it has been assumed that the $W = F(R)$ relation is the relation for an isotope with the mass 14.07 AMU. There exists, however, a statistical error in $W = F(R)$ in the interval $7.5 < R < 12 \text{ mm}$ which makes this mass value somewhat uncertain. This error amounts to 0.09 AMU.

The total statistical error in the mass scale is obtained by quadratically summing the error originating from the W-REL relation 0.07 AMU and the error given above, 0.09 AMU. The value will be 0.11 AMU, which constitutes the uncertainty in the mass scale in Fig. 7.

VII. The results.

1. Isotopic composition of oxygen.

Fig. 13 shows the distribution of the masses of 80 oxygen nuclei. The best fit to the distribution with the use of $\sigma = 0.50$ AMU gives:

$$(^{14}\text{O} + ^{15}\text{O}) : ^{16}\text{O} : ^{17}\text{O} : ^{18}\text{O} = 4:66:4:6$$

The numbers of the ^{15}O and ^{17}O particles must be looked upon as upper limits since the existence of tails in the ^{16}O -distribution cannot be completely excluded.

The isotopic composition has been extrapolated to the top of the atmosphere with standard methods. The cross-sections have been derived from data in a paper by Silberberg and Tsao (1973), and from measurements of nucleus-nucleus cross sections by Lindstrom et al. (1974).

Table 3 shows the obtained quotients $^{15}\text{O}/\text{O}$, $^{17}\text{O}/\text{O}$ and $^{18}\text{O}/\text{O}$ in the detector and at the top of the atmosphere. The mean mass is, at the detector, equal to 16.15 AMU, and at the top of the atmosphere 16.20 AMU. Theoretical values calculated by Tsao et al. (1973) are also shown in the Table. The values are valid for relativistic oxygen from a source with a normal stellar composition. The path length distribution through interstellar matter was taken to be of the form $\exp(-0.24 x)$ with a linear rise between 0 and 1 g/cm².

The experimental abundance of ^{18}O in Table 3 is high compared with the value calculated by Tsao et al. The difference is not significant and cannot be taken as evidence that the abundance of ^{18}O in the source is higher than in normal stellar atmospheres

Table 3

	Detector	Top of atmosphere	Calculated Tsao et al.
^{15}O	0.05 ± 0.03	---	---
^{17}O	0.05 ± 0.03	0.05 ± 0.03	0.025
^{18}O	0.08 ± 0.03	0.08 ± 0.03	0.02

Only a few other experimental values of the isotopic composition of oxygen are published. In many isotope measurements, it has been common to use the mean mass of oxygen for calibration purposes. The mean mass has then often been set equal to 16.00 AMU, which is slightly smaller than the value 16.15 AMU obtained in this investigation.

The group from Goddard Space Flight Center has published results from measurements with a counter telescope exposed in a balloon flight. Hagen et al. (1975) give the ratios $^{17}\text{O}/\text{O} = 0.10 \pm 0.03$ and $^{18}\text{O}/\text{O} = 0.07 \pm 0.01$ for the registered particles. Fisher et al. (1976) give the mean mass of oxygen equal to 16.08 ± 0.05 AMU with a possible systematic error of less than 0.2 AMU. The same authors quote the ratios $^{17}\text{O}/\text{O} \leq 0.065$ and $^{18}\text{O}/\text{O} = 0.025 \pm 0.05$. In a measurement by the New Hampshire group with a balloon-borne counter telescope, the ^{18}O abundance was estimated to $^{18}\text{O}/\text{O} < 0.015$ (Prezler et al. 1975).

2. Isotopic composition of nitrogen.

The mass spectrum of the nitrogen particles shown in Figure 14 gives the composition $^{14}\text{N}:^{15}\text{N} = 16:9$. The values are obtained from the best fit of two Gaussian distributions with $\sigma = 0.46$ AMU. The ratio $^{15}\text{N}/(^{15}\text{N}+^{14}\text{N})$ is 0.36 with a statistical error of ± 0.10 . The uncertainty in the mass scale contributes with an error which is less than ± 0.04 . After extrapolation to the top of the atmo-

sphere, the ratio $^{15}\text{N}/(^{15}\text{N} + ^{14}\text{N})$ is 0.33 ± 0.09 .

In Fig. 17, the result is compared with ratios obtained from other investigations. Some of these ratios are not extrapolated to the top of the atmosphere. However, an extrapolation does not change the ratio by a large amount, which can be seen from the figure above. The curves in the Figure are calculated values by Meneguzzi et al. (1971). The upper curve is based on the assumption that the source of the radiation is devoid of nitrogen. The lower curve is calculated for the source containing normal stellar abundance of nitrogen, i.e. $\text{N}/\text{CNO} = 0.05$. Also marked in the Figure is a value by Shapiro (1975) calculated for relativistic particles with $\text{N}/\text{CNO} = 0.05$. The experimental value in this investigation supports the assumption that nitrogen is present in the source to an amount which is approximately in agreement with the composition of the solar system.

Acknowledgments.

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Figure captions

- Figure 1. The optical part of the photometer.
- Figure 2. The comparison between plate factors from the range interval 0-1 mm and 1-12 mm.
- Figure 3. The comparison between plate factors for the oxygen tracks and the carbon-nitrogen tracks.
- Figure 4. The dip correction term $F(\alpha)$ for carbon and oxygen.
- Figure 5. The normalized W-values as a function of the edge distance.
- Figure 6. The mass spectrum for oxygen. The curve is a Gaussian distribution with $\sigma = 0.50$ AMU.
- Figure 7. The mass spectrum for nitrogen.
- Figure 8. a) The separation ΔW between the W-R relations for ^{16}O and ^{17}O .
b) The standard deviation of the W-measurement as a function of range.
- Figure 9. a) The mass resolution for one mm long track segments as a function of range.
b) The mass resolution as a function of measured length.
- Figure 10. The distribution of measured W-values around the W-R relation. The large histogram is for ^{16}O and the small one for $^{16}\text{O} + ^{17}\text{O} + ^{18}\text{O}$.
- Figure 11. Comparison of mass values for oxygen calculated with and without the exclusion of W-values outside $\pm 2\sigma$.

Figure 12. The distribution of the sums S , $^{15}\text{O} + ^{17}\text{O} + ^{18}\text{O}$ are especially indicated. The curve is the expected χ^2 -distribution.

Figure 13. The distribution of plate W -levels. The large histogram is for ^{16}O and the small for $^{15}\text{O} + ^{17}\text{O} + ^{18}\text{O}$. The curves are Gaussian distributions with $\sigma = 1.00$.

Figure 14. The distribution of differences between mass values calculated from the range interval 1-6 mm and 6-12 mm. Specially indicated are $^{15}\text{O} + ^{17}\text{O} + ^{18}\text{O}$. The curve is the expected Gaussian distribution with $\sigma = 1.0$ AMU.

Figure 15. The relation between track width W and restricted energy loss REL for oxygen and carbon.

Figure 16. The calculated mean mass \bar{M} for 16 nitrogen particles as a function of range. The curve is based on the $W=F(R)$ relation and the points are based on mean values of W .

Figure 17. The ratio $^{15}\text{N}/\text{N}$ as a function of particle energy.

The points, a-l, are experimental values.

a: Beaujean and Enge (1972).

b: Garzia-Munoz et al. (1974).

c: Webber et al. (1973).

d: Prezler et al. (1975).

e: This work.

f: Hagen et al. (1976).

g: Fisher et al. (1975).

h and i: Webber et al. (1974).

j and k: Dwyer et al. (1975).

l: Juliusson (1975).

The line marked m, is a calculated value by Shapiro (1975) assuming $N/CNO = 0.05$ in the source. The curves are calculated values by Meneguzzi et al. (1977) for two cases $N/CNO = 0$ and $N/CNO = 0.05$ in the source.

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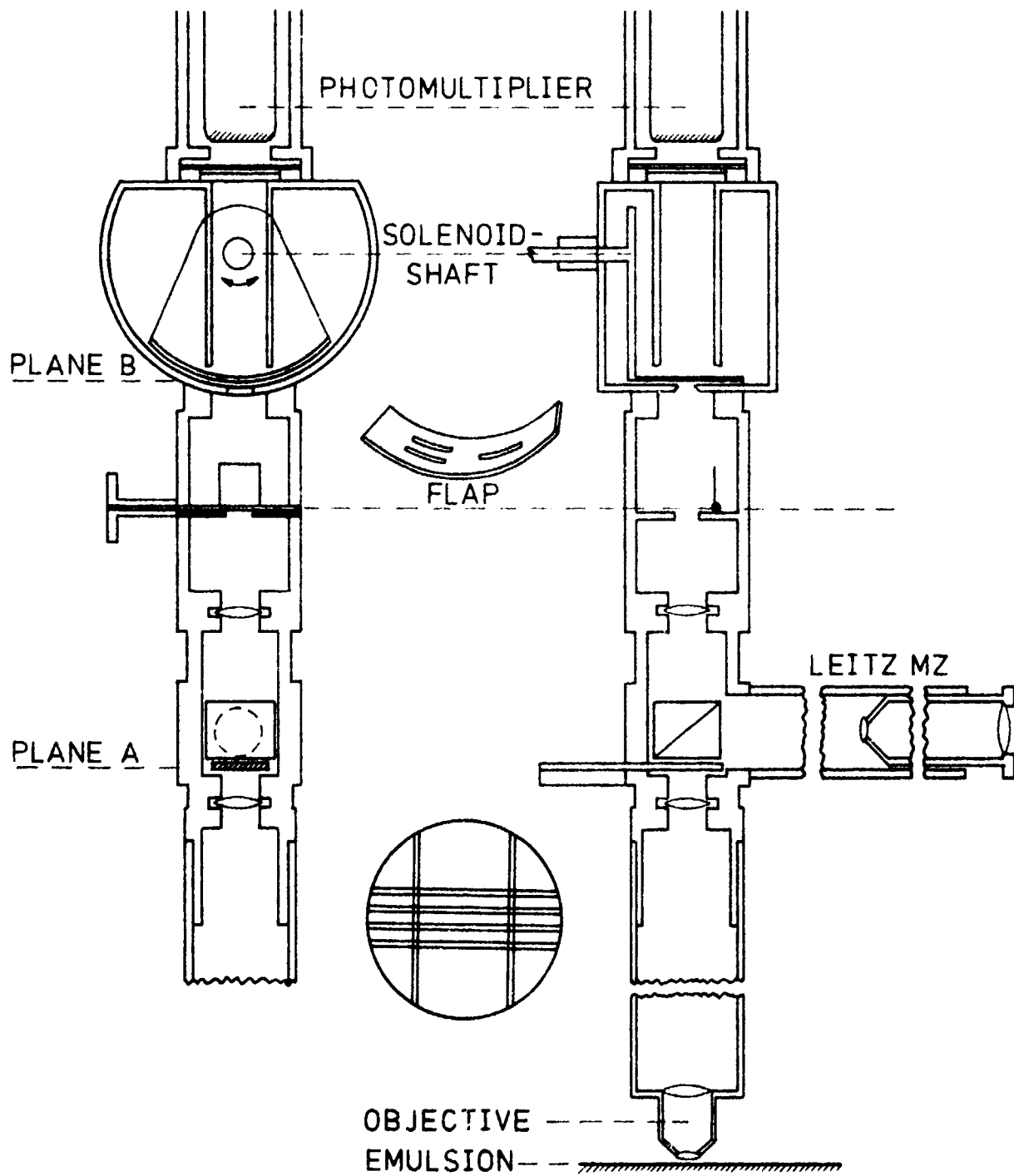


FIG. 1

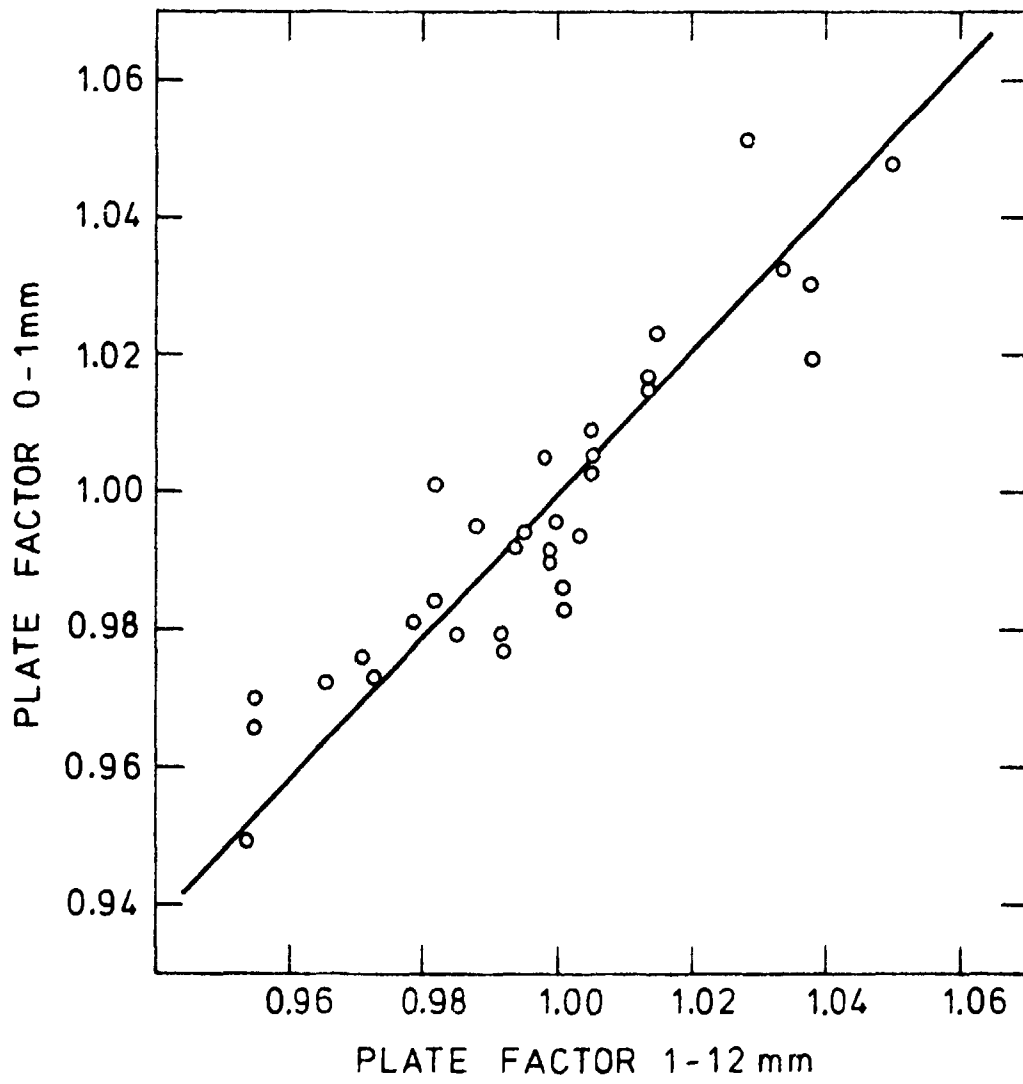


FIG. 2

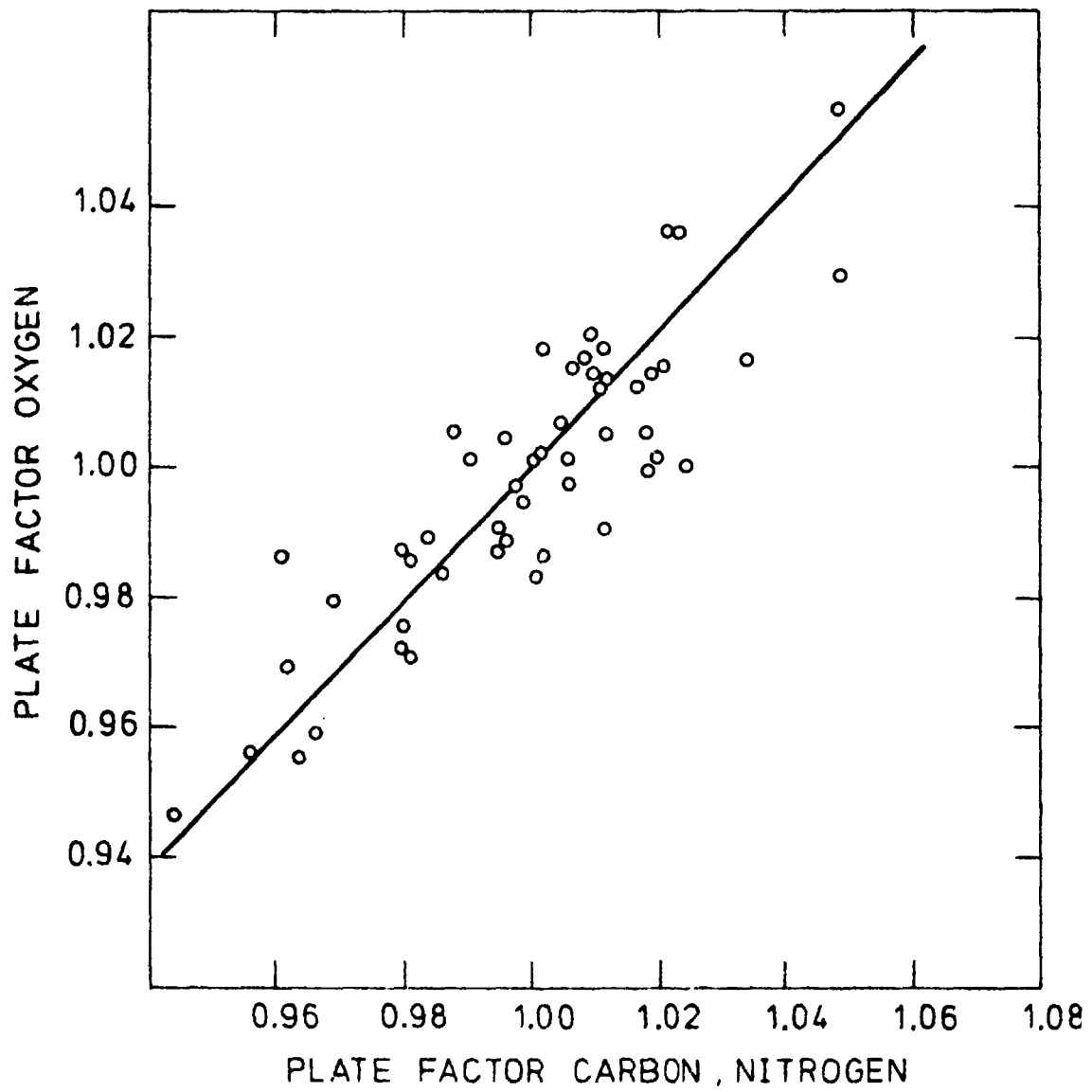


FIG. 3

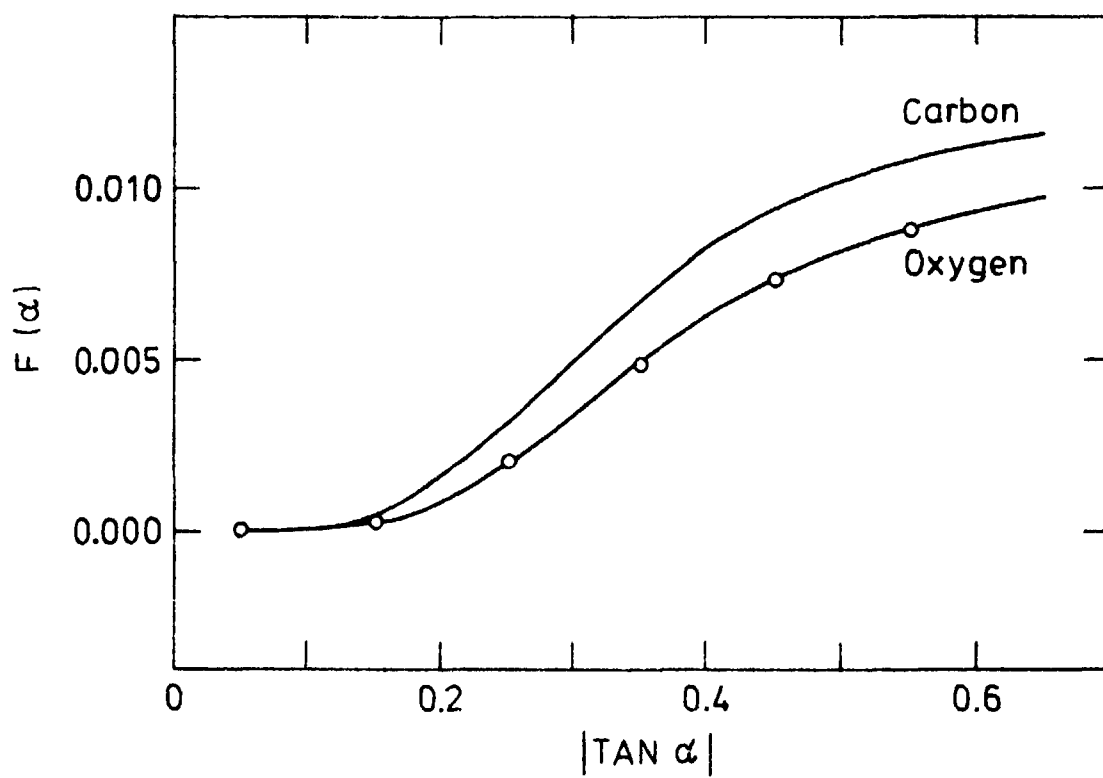


FIG. 4

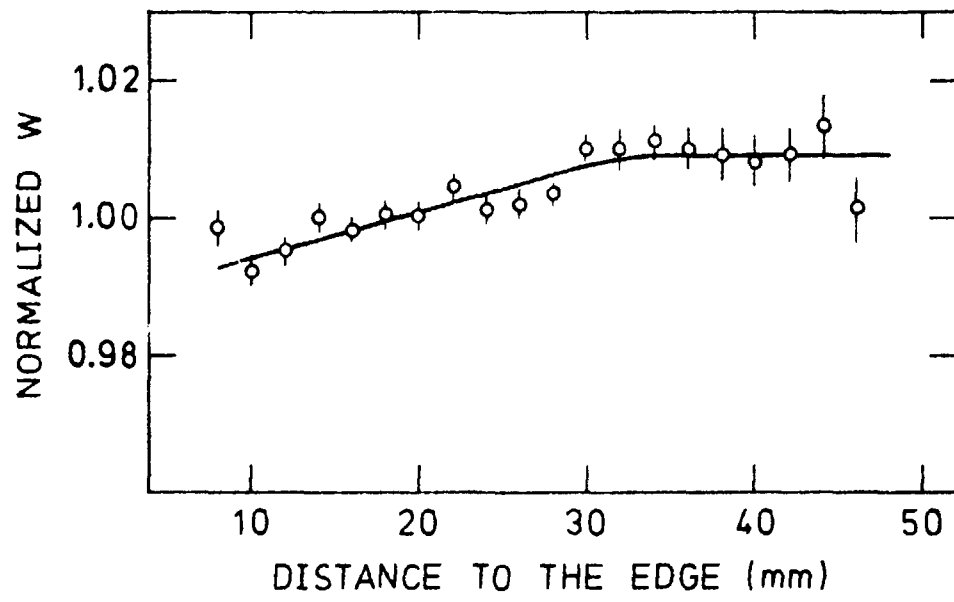


FIG. 5

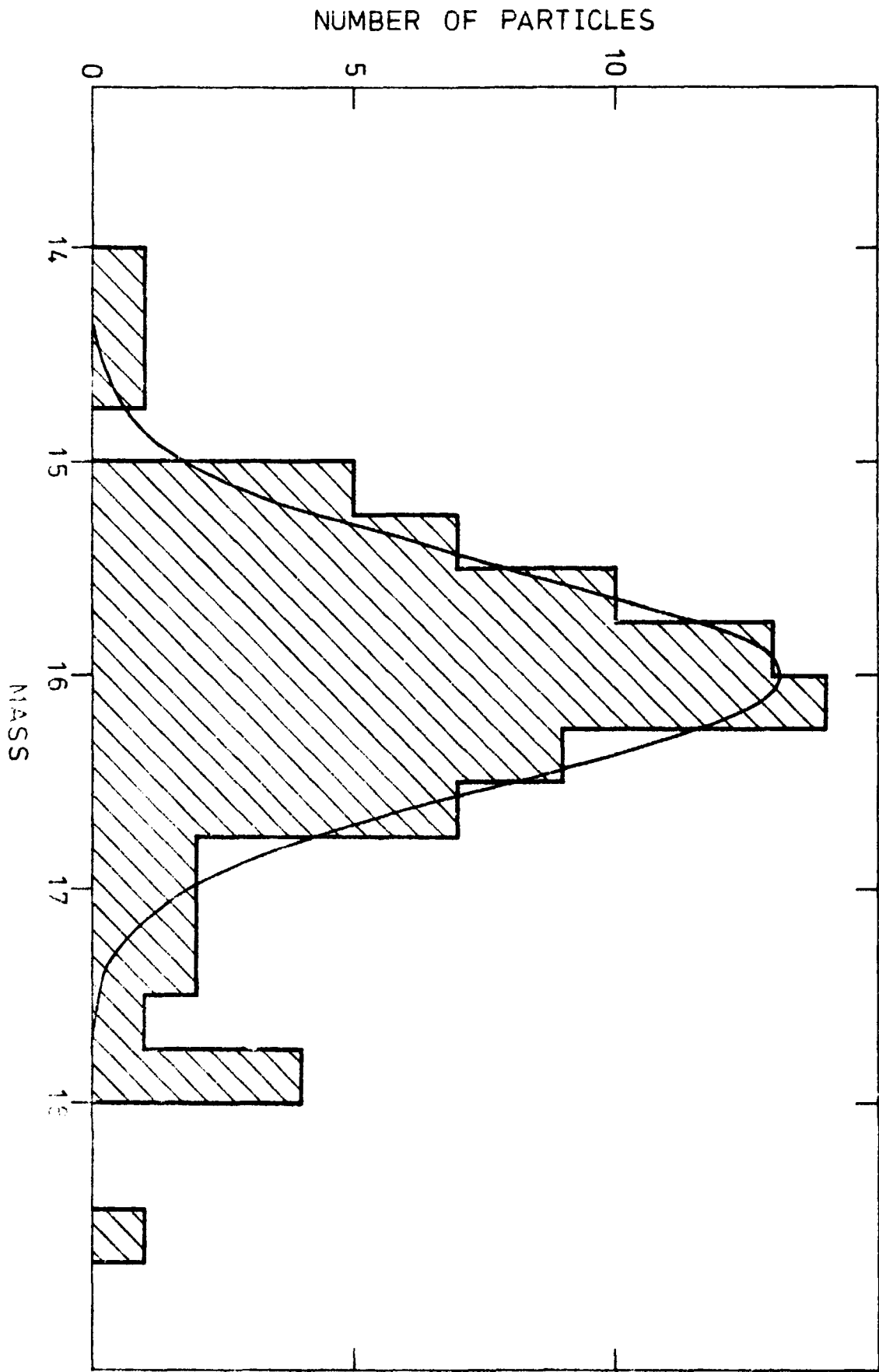


FIG. 6

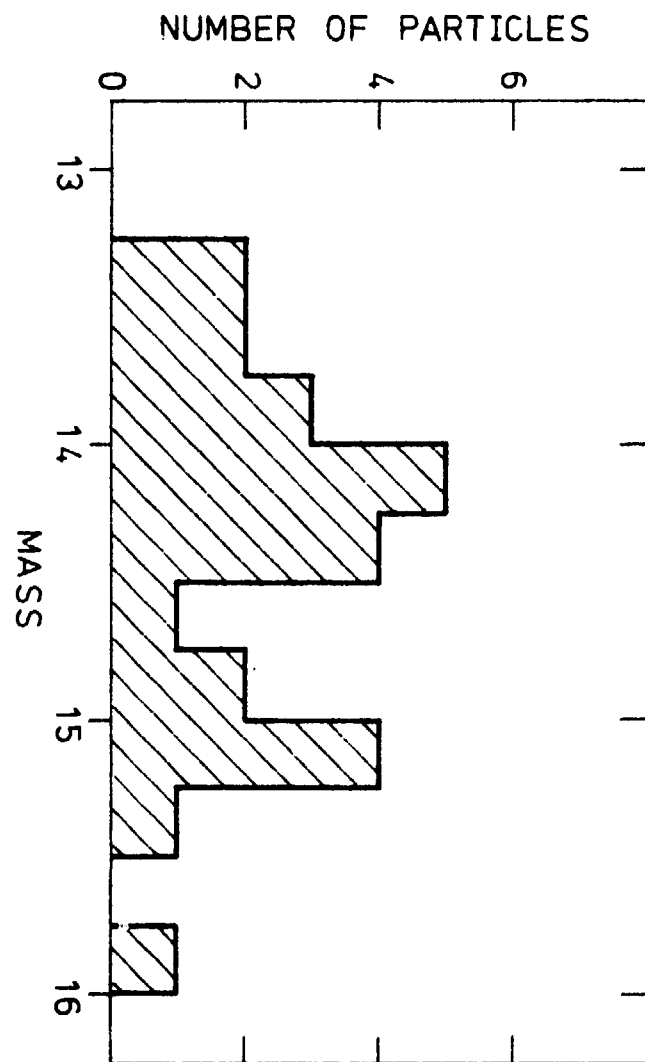


FIG. 7

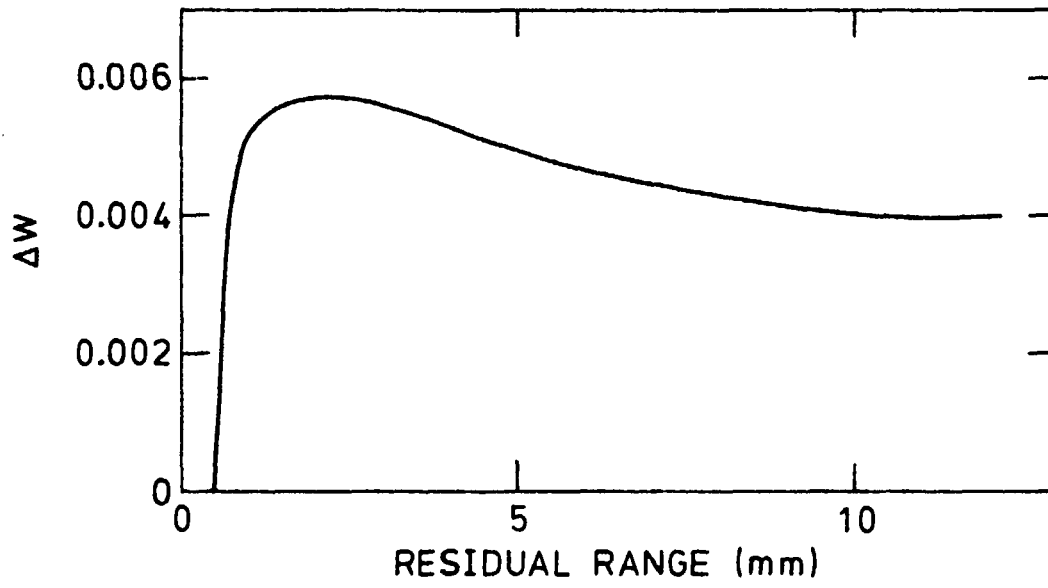


FIG. 3 A

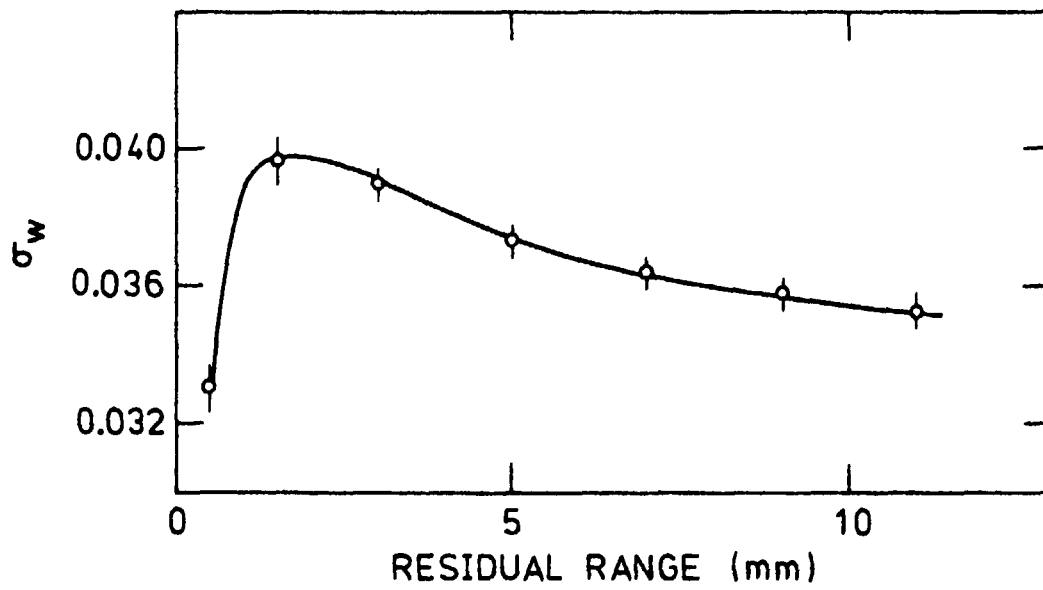


FIG. 3 B

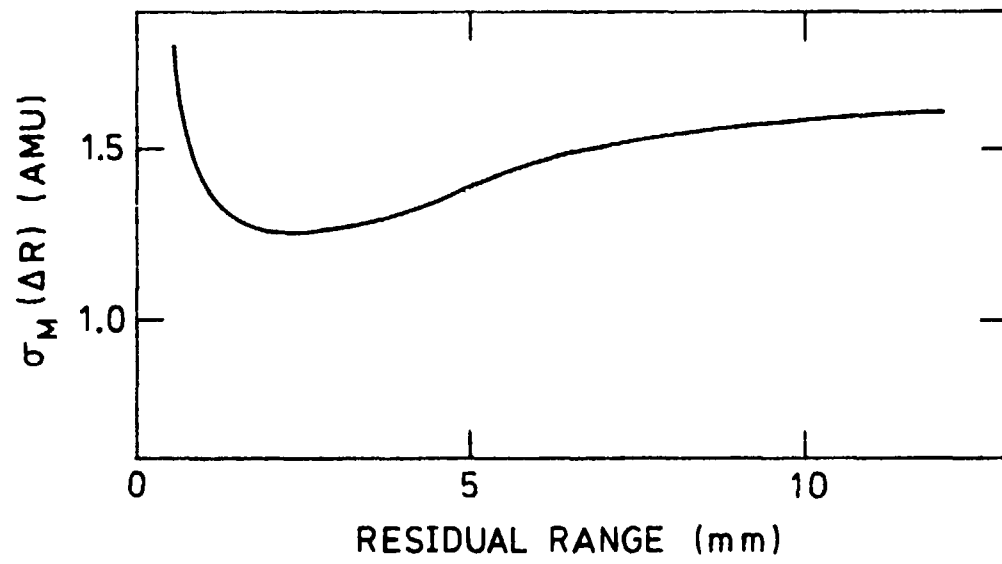


FIG. 9 A

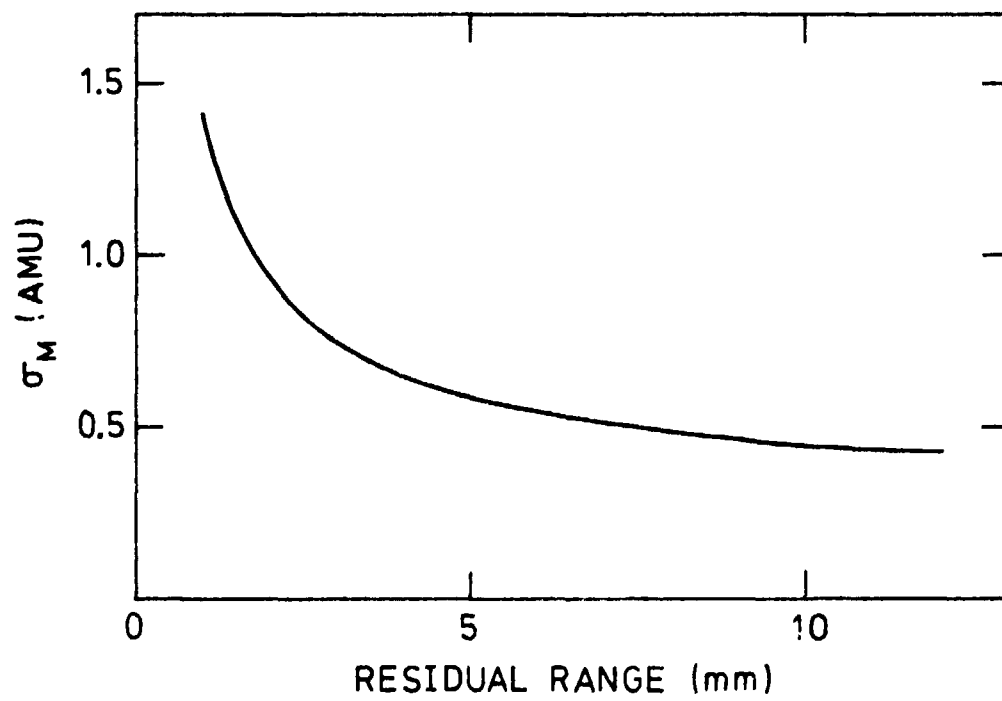


FIG. 9 B

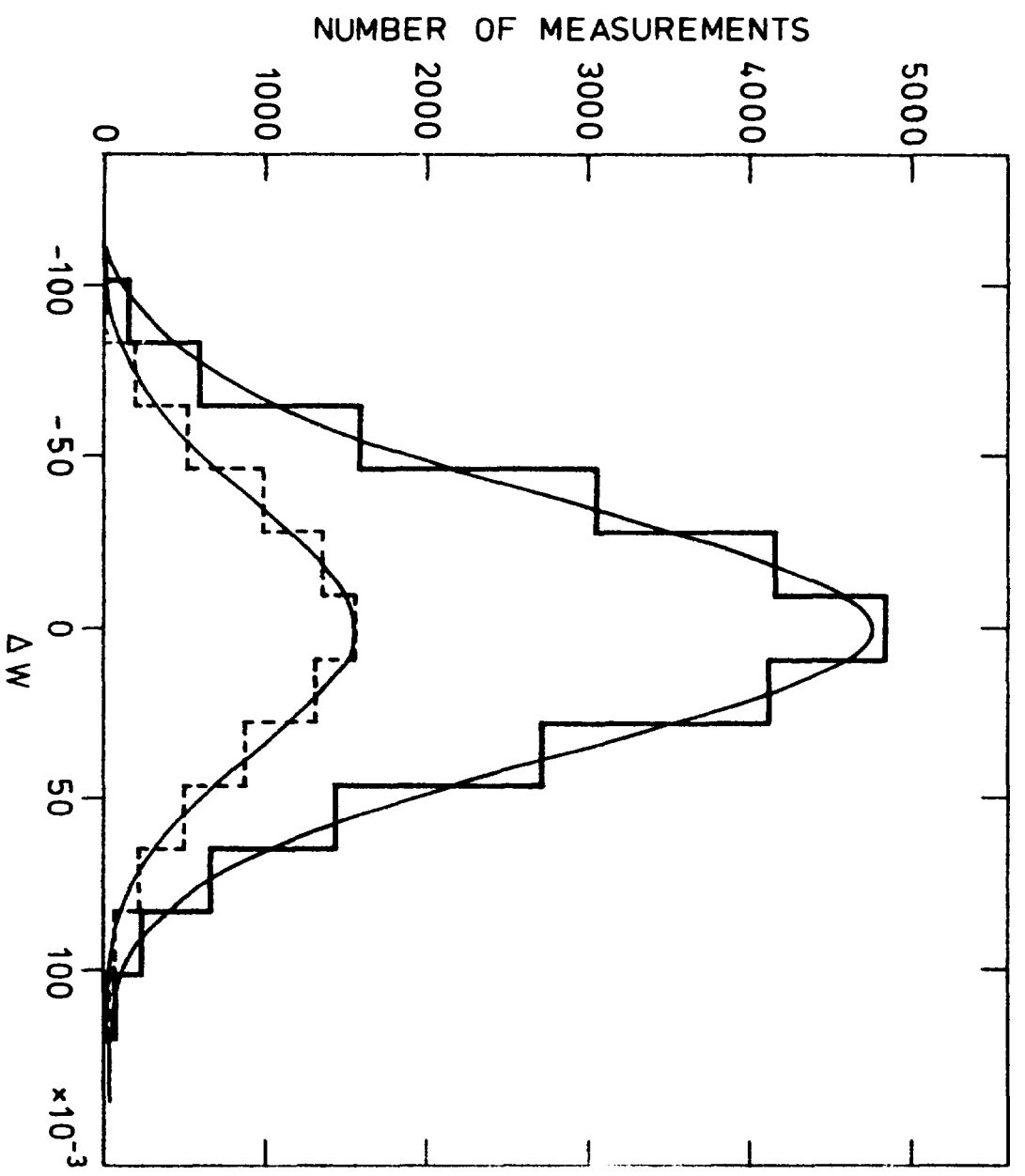


Fig. 10

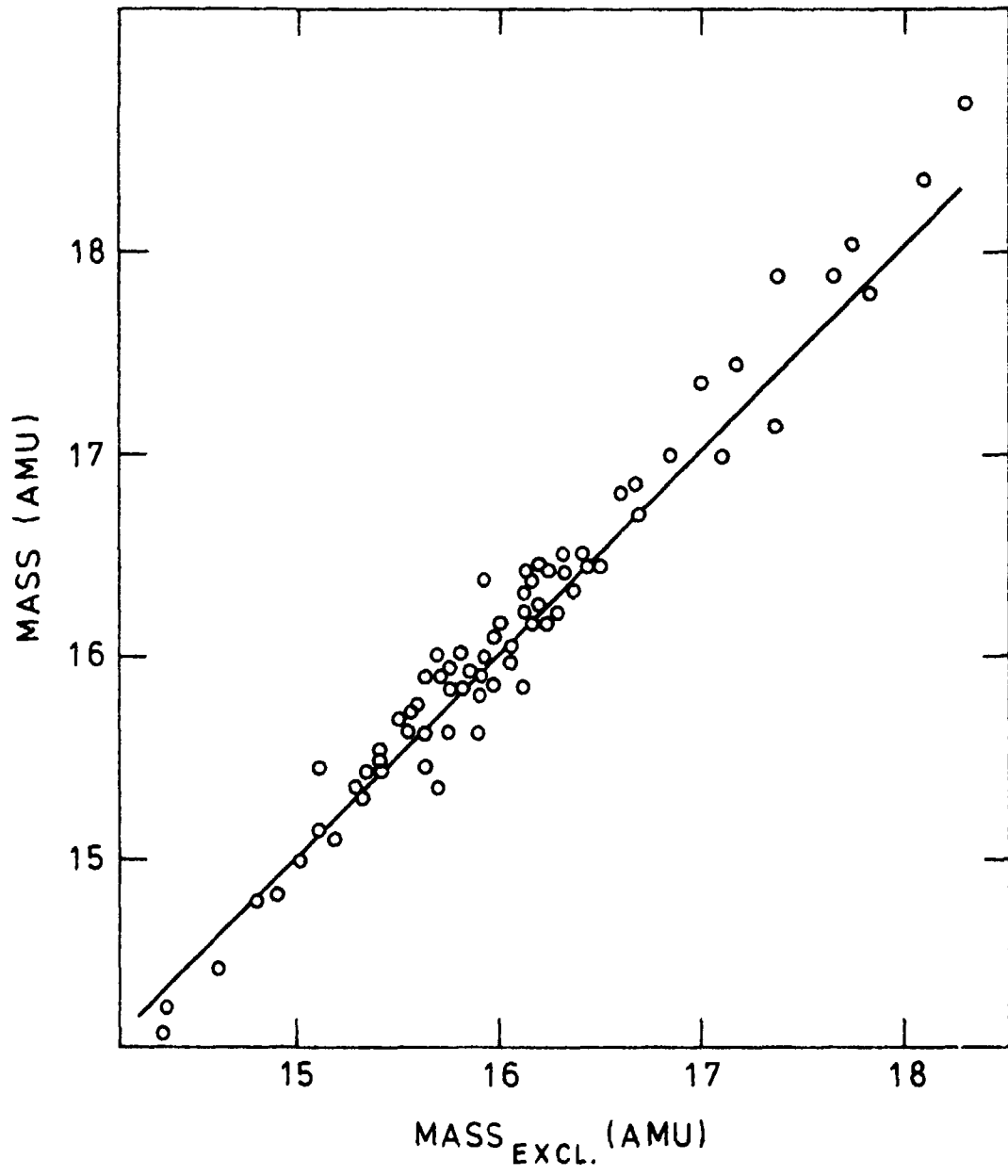


FIG. 11

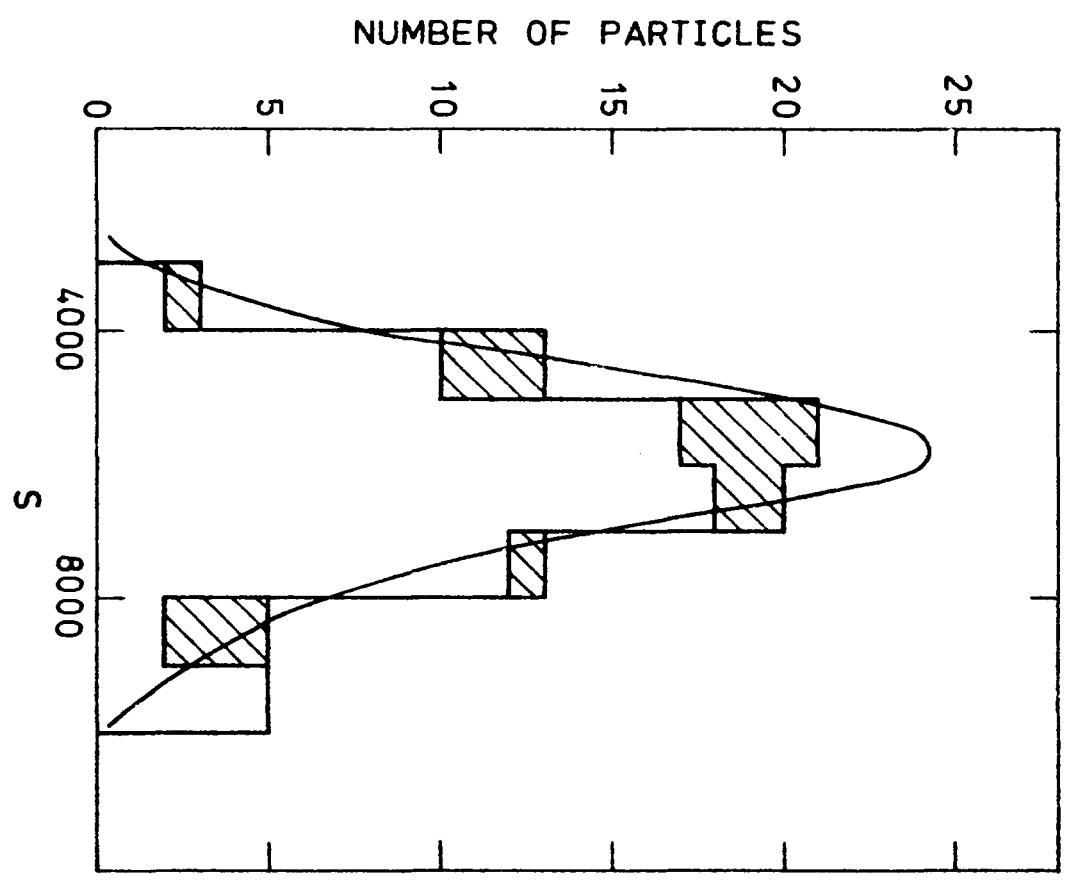


Fig. 12

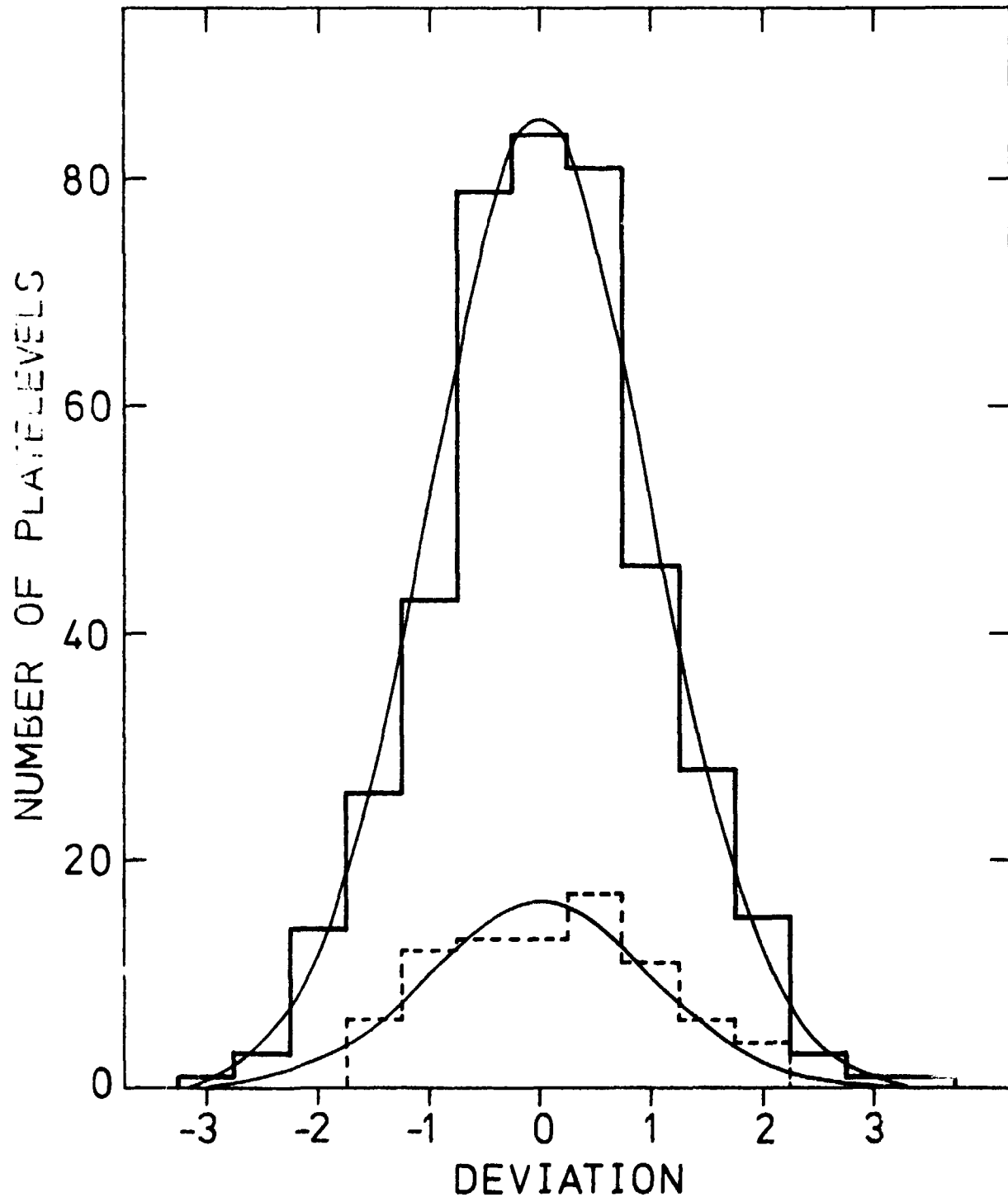


FIG. 13

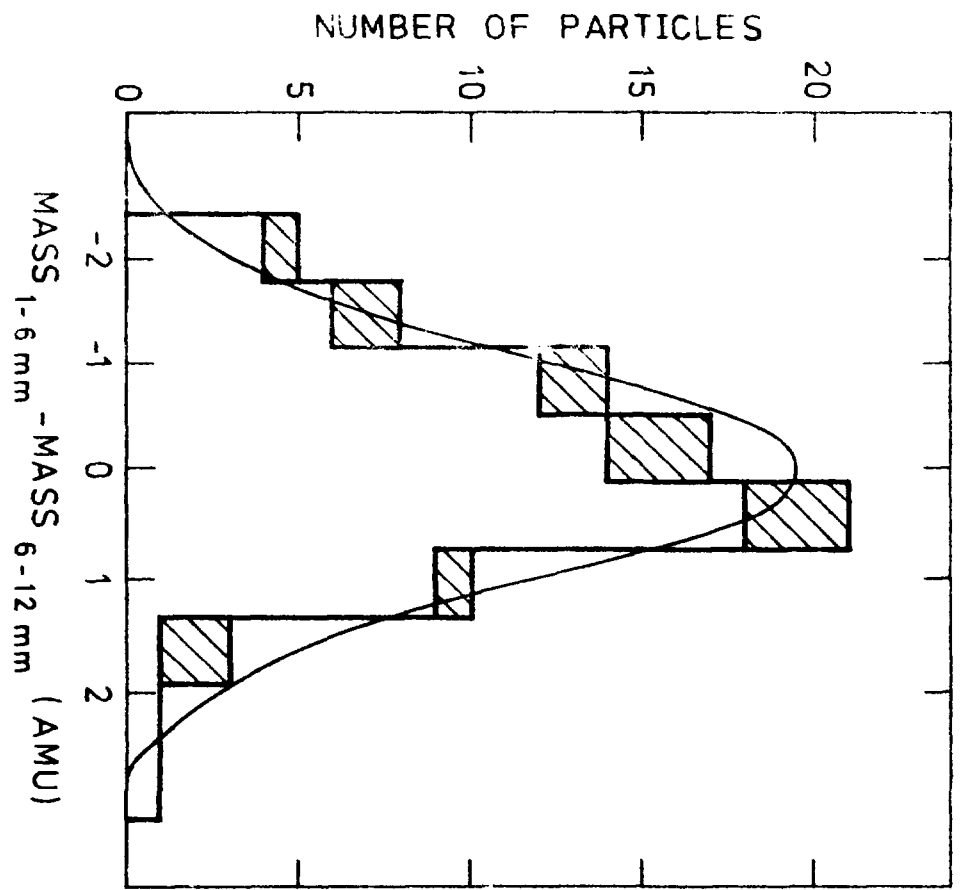


FIG. 14

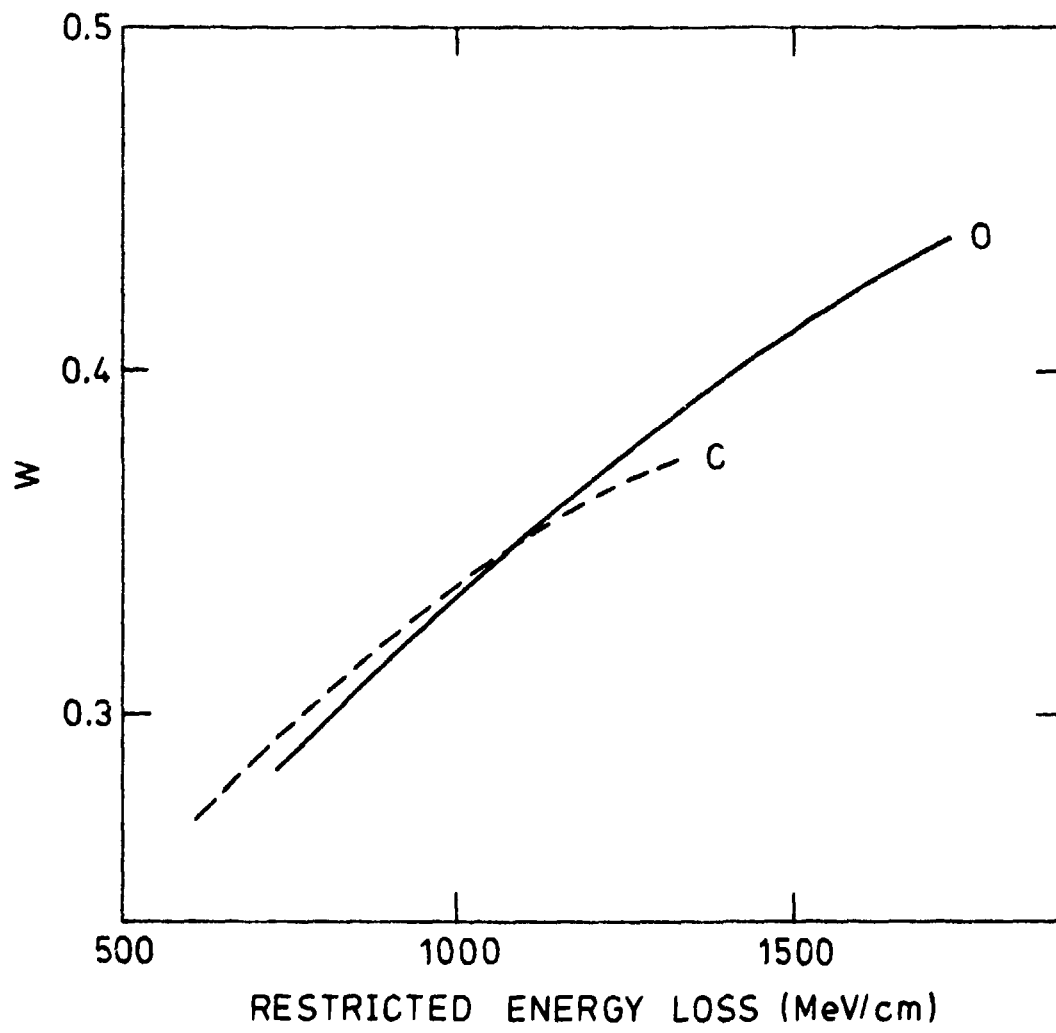


FIG. 15

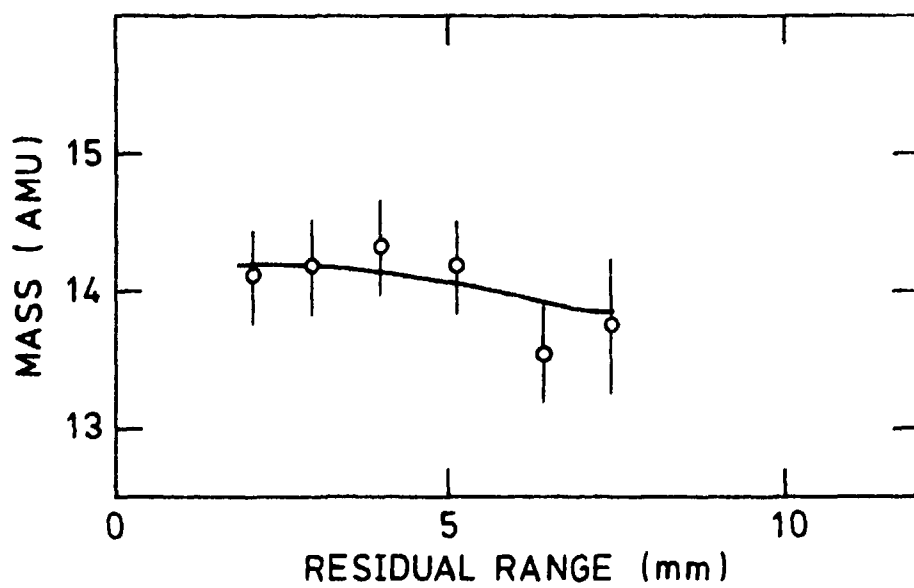


FIG. 16

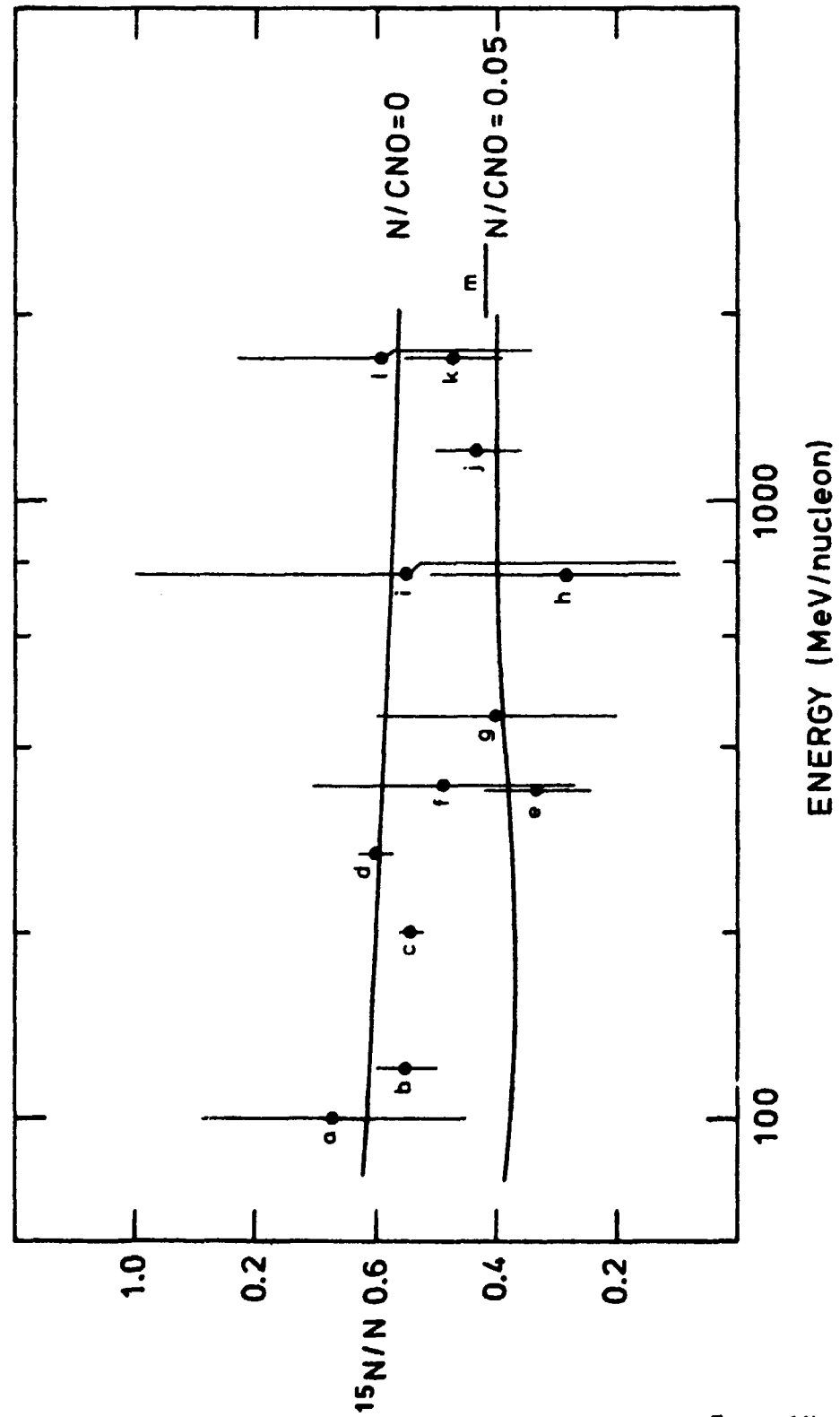


Fig. 17