COSMIC AND SUBATOMIC PHYSICS REPORT
LUIP 7811
1978-12-07
LUNFD6/(NFFK-7011)1-36(1978).

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Abstract.

An experimental investigation of the isotopic composition of cosmic ray nitrogen and oxygen is reported. The detector is a stack of nuclear emulsions exposed at about 3 g/cm^2 atmospheric depth. The mass determinations are based on photometric track width measurements on stopping nuclei. The standard deviation of the mass measurements is 0.46 AMU for nitrogen and 0.50 AMU for oxygen. The energy of the measured nuclei falls in the interval 220-450 MeV/nucleon at the top of the atmosphere.

The measured isotopic quotients have been extrapolated to near interstellar space with standard methods. The extrapolated quotients are ^{15}N/N = 0.34±0.10, ^{17}O/O = 0.02±0,03, ^{18}O/O = = 0.07±0.03. The nitrogen quotient extrapolated to the cosmic ray source shows that the nitrogen-oxygen abundances ratio is approximately the same in the source as in the solar system. The result has been compared with different hypotheses about the source composition and is found to be in best agreement with a hypothesis, which states that source matter has approximately the composition of the solar system and that a selection mechanism depending on the atomic properties of the elements is working in the source.

1. Introduction.

Measurements of the isotopic composition of cosmic ray nitrogen and oxygen give important information about the processes in which cosmic ray matter has been involved prior to acceleration and thereby also about the origin of the radiation. The main question concerning nitrogen is whether it is present in the cosmic ray source in such amounts that the N/CNO ratio is approximately the same as in the solar system, or whether source matter is strongly depleted in nitrogen with the N/CNO quotient much smaller than that of the solar system. The two possibilities give different answers to the question about the origin of the radiation.

If the source abundance of nitrogen is found to be very small, it can be assumed that a large fraction of the heavy elements in the radiation are nuclei which originate in the mantle of an evolved supernova and which have been accelerated in the supernova remnant before the remnant became mixed to a large degree with surrounding interstellar matter. (Arnett and Schramm 1973; Hainebach et al., 1976). The mantle of an evolved supernova is assumed not to contain nitrogen.

If the N/CNO ratio is similar to the solar system ratio, it is not unreasonable to assume that the source has approximately the composition of the solar system. The relative overabundance of the heavy elements is in this case explained by preferential selection of the heavy nuclei in the source (Kristiansson 1971, 1974; Havnes 1971; Cassé and Goret 1973, 1978).

The existence of nitrogen in the source can suitably be determined by measuring the quotient $^{15}N/(^{14}N + {}^{15}N)$ in the radiation reaching the solar system. This quotient, which depends on the source composition and on the production of ^{14}N and ^{15}N in nuclear reactions during the transport of the radiation is, according to calculations, equal to about 0.6 if nitrogen is very underabundant in the source, and about 0.4 if nitrogen is present in the same amount as in the solar system. Most of the investigations of the nitrogen isotopes so far reported are made with counter telscopes. The main part of the measurements seems to give a value of the quotient below 0.6. The uncertainty is, however, still large concerning the correct value of the quotient.

There are reasons to believe that ^{16}O is the dominating isotope in the oxygen reaching us and that the small amounts of ^{17}O and ^{18}O, which are present in the radiation, are produced during the passage of the radiation through interstellar matter. There are, however, still uncertain indications that some of the heavier elements, especially neon, show an overabundance of the most neutron rich isotope (Fisher et al., 1976; Prezler et al. 1975). If these observations are confirmed we cannot exclude the possibility that also oxygen can show an overabundance of the most neutron rich isotope. A high proportion of ^{18}O can possibly depend on helium burning of ^{14}N under such temperature and density conditions that the burning stops at ^{18}O (Arnou and Beelen, 1974). Finally, in many cosmic ray isotope measurements oxygen has been used as a reference element for the mass scale, which implies that knowledge of the isotopic composition is important. Thus several reasons exist, which call for studies of the isotopic composition of oxygen.

In this paper we report measurements of the isotopic composition of cosmic ray nitrogen and oxygen in a stack of nuclear emulsions, which was exposed to the primary radiation in a high altitude balloon flight in northern Canada. The exposure, the detector stack and the method of mass measurements are described. We discuss the mass resolution and the method of calibrating the nitrogen mass scale. Further, we describe the extrapolation of the isotopic quotients to the source and make comparisons with other measurements. Finally we compare our results with the predictions of the different hypotheses about the origin of the radiation and conclusions are drawn about the cosmic ray source.

2. The experiment.

The particle detector used in the investigation is a stack of 61 Ilford G5 nuclear emulsions, each one having the dimensions 10x10x0.06 cm^3. The stack was exposed in a balloon flight from Fort Churchill, Canada, in June 1970 at an atmospheric depth of 2.6 - 3.4 g/cm^2. The packing material, which the particles penetrated, was in the mean 2.0 g/cm^2. The time of exposure was 8 hours. The emulsions were processed according to the temperature cycle method with the dry hot developing stage at 20°C.

The blob density for relativistic singly-charged particles was 18 blobs/100 μm.

Scanning for tracks of stopping heavy nuclei was performed throughout the stack. All tracks with a dip angle less than 37° in the unprocessed emulsion were preliminarily measured with a nuclear track photometer to select particles with $Z = 6$, 7 and 8. The carbon nuclei were included for calibration purposes.

The tracks selected in the preliminary measurements were all traced backwards through the stack in order to exclude all nuclei which had taken part in nuclear interactions in the stack. The tracks had to fulfil three mainly geometrical conditions in order to be accepted for the measurements on which the mass determinations were based.

1. Only tracks with dip angles in the interval 4.6°-33° were measured.
2. At least 9 mm of the track in the measured residual range interval $1<R<12$ mm must fall more than 8 mm from the edge of the pellicles.
3. The zenith angle must be less than 70°. This excludes particles which have passed more than 9 g/cm^2 of air.

The determination of the mass of a particle is based on the relations between track width and residual range in the range interval $1<R<12$ mm. For the measurement of the track widths we used a nuclear track photometer. The construction of this photometer is described by Jönsson et al. (1970a). We only want to emphasize that the size of the central slit, which defines the area of measurement, corresponds to an area 33x4.0 (μm)^2 in the object plane. The slit dimensions have been chosen to give both sufficient mass resolution and a reasonable speed in the track width measurements.

The width of a track at a certain residual range depends on the charge and the mass of the particle producing the track. The track width measured with the photometer is, however, also influenced by different effects in the emulsion plates. These emulsion effects were eliminated by a correction procedure, which is described elsewhere (Jacobsson, 1977).

The mass M of a particle is calculated by a least squares procedure. The mean relation between track width and residual range is at first determined for all particles of the same charge. For $1 < R < 12$ mm the relation can be approximated by a function

$$W(R) = \sum_{1}^{5} a_i \cdot R^{b_i}$$

where W(R) is the track width at the residual range R. The constants a_i are determined by a best fit to the experimental mean track width-range relation. The fitting has shown to be sufficiently good if $i = 1\text{-}5$ with $b_i = 0, 1/2, 1, 2$ and 3.

W(R) is the track width-range relation for a particle with the mass $\bar{M}$ equal to the mean mass of the measured particles. The track width-range relation for a particle with the mass M can be written

$$W(R,M) = \sum_{1}^{5} a_i \left(R \cdot \frac{\bar{M}}{M}\right)^{b_i}$$

according to basic ionization theory. The mass is calculated by fitting W(R,M) to the experimental width values of the track with $\bar{M}/M$ as the free parameter. The calculations give only mass values relative to the mean mass of the measured particles. The absolute mass scale must be determined differently. The computation procedure is described in the paper by Jönsson et al. (1970b).

The track width was 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 available number of width values of a track is 360. All nitrogen and oxygen tracks fulfilling the selection criteria were measured, whereas only 25 ^{12}C-tracks were included in the investigation for calibration purposes. All nitrogen tracks were measured at least twice. As the oxygen tracks were initially also intended for calibration purposes only about one half of them were measured twice. For a track which was measured twice or more, the mean value of the measurements was used.

Measurements disturbed by dark spots in the emulsion or by crossing tracks were excluded. Their number amounts to about 1%. About 7% of the measurements were excluded because they were made closer to the glass or the surface of the emulsion than 10 µm in the processed emulsion. This exclusion of measurements has given rise to a fourth selection criterion whose purpose is to guarantee a sufficient precision in the mass determination:

4. The number of accepted width measurements for a track in the residual range interval $1 < R < 12$ mm must be greater than 250.

It must be stressed that the selection criteria are geometrical in nature and independent of the particle mass and can have no systematic influence on the measured isotopic ratios.

3. Mass spectra and expected errors in the mass determinations.

The mass distributions of the nitrogen and the oxygen particles are shown in Figures 1 and 2. The mass scale of Figure 1 cannot be accurately fixed exclusively from the experimental mass distribution, owing to the small number of measured particles and to the uncertainty concerning which stable and unstable isotopes possibly exist in the mass spectrum. Therefore the mass scale has been determined by a special method of calibration. The mass scale in Figure 2 is based upon the assumption that the main peak is a ^{16}O-distribution. The curve in the figure is a Gaussian with the standard deviation $\sigma = 0.50$ AMU.

Calibration of the nitrogen mass scale: The mass scale in Figure 1 is determined by an interpolation procedure based on the experimental track width-range relations of ^{12}C and ^{16}O. The starting point for this interpolation is the fact that the track width can be plotted as a function of the ionization parameter restricted energy loss, REL, and that this track width-REL relation is, in the first approximation, independent of the particle charge (Jensen et al., 1976).

Figure 3 shows the relation between track width and restricted energy loss for ^{12}C and ^{16}O, respectively. The ^{16}O-curve is based on the particles of the main peak in Figure 2. The ^{12}C-curve is based on measurements of ^{12}C tracks identified in a study of the isotopic composition of carbon in the same emulsion stack (Bjerle and Herrström, 1976). The restricted energy loss is computed from a formula given by Barkas (1963). The relation for ^{14}N has been obtained by a linear interpolation in the interval 730 MeV/cm < REL < 1330 MeV/cm. The mass scale of the measured nitrogen nuclei is established in a comparison of the measured track width-range relation for nitrogen with the ^{14}N relation obtained by the interpolation. The total error in the position of the nitrogen mass scale has been estimated to 0.11 AMU. This error is purely statistical. We believe, that a possible systematic error from the interpolation procedure is very small compared to the statistical error. A discussion of the calibration procedure is published elsewhere (Jacobsson and Jönsson, 1978).

Expected errors in the mass determinations: As the distributions do not show a complete separation between the different isotopes of the same elements, a statistical procedure has to be used for the estimate of the most probable number of the different nuclides in the samples. The analysis requires a knowledge of the expected mass resolution. This is calculated according to a method originally applied by Malmqvist (1970). The main factors, which determine the mass resolution, are:

1. the difference between the track width-residual range relations of consecutive isotopes.
2. the standard deviation of the track width measurements and the number of measurements on which the mass determination is based.
3. errors originating in the corrections of the measurements.
4. fluctuations in the response of the photometer.

Figure 4 shows the calculated, expected standard deviation in a mass determination of an oxygen nucleus as a function of measured track length. Only the statistical spread of the track width measurements and the mass resolution have been considered. It is furthermore assumed that no measurements are excluded. Figure 4 shows that it is reasonable to stop measuring at a residual range of about 12 mm.

In Table I we show the different contributions to the error in the mass determination when track lengths of 12 mm residual range are measured. The first line gives the standard deviation expected from the mass resolution and the statistical spread of the track width measurements. In the second line we have considered that, in the mean, the number of accepted track width measurements is less than the nominal number by 9% due to exclusions and give the contribution to the error from these exclusions. In the third line we have given the estimated error from the correction procedure and in the last line the errors from the fluctuation in the photometer response. This error is smaller for nitrogen than for oxygen because all nitrogen tracks have been measured at least twice, whereas only some of the oxygen tracks were measured more than once.

The analysis of the errors has thus shown that a mass distribution with a standard deviation amounting to 0.50 AMU for oxygen and 0.46 AMU for nitrogen can be expected. As can be seen from Figure 2, the expected distribution for ^{16}O is in good agreement with the width of the main peak in the mass spectrum. A similar investigation of the standard deviation in a measurement of the carbon isotopes also shows good agreement between the expected standard deviation C = 0.42 AMU, and the width of the experimental ^{12}C-distribution (Bjarle and Herrström, 1976). There are thus reasons to believe that the computed standard deviation for nitrogen describes well the widths of the mass distributions of the nitrogen isotopes.

4. Extrapolation to near interstellar space and comparison with other measurements,

The mass spectrum of the nitrogen nuclei in Figure 1 gives the composition $^{14}N : {}^{15}N = 16:9$. The numbers are obtained from a fit of two Gaussian distributions with $\sigma = 0.46$ AMU. The ratio $^{15}N/(^{14}N + {}^{15}N)$ 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 in the quotient.

A similar fit to the distribution of the oxygen nuclei in Figure 2 with $\sigma = 0.50$ AMU gives $(^{14}O + {}^{15}O):{}^{16}O:{}^{17}O:{}^{18}O = 4:66:4:6$. The numbers of ^{15}O and ^{17}O nuclei must be looked upon as upper limits, since the existence of non-Gaussian tails in the ^{16}O-distribution cannot be excluded. Some information about these tails can be obtained from ^{15}O. Extrapolation calculations through the atmosphere and the stack show that one can expect two ^{15}O-nuclei in the measured spectrum. If we assume this and that the ^{16}O-distribution is symmetrical, a better number estimate would be $^{15}O : {}^{16}O : {}^{17}O : {}^{18}O = 2 : 70 : 2 : 6$. The ratio $(^{17}O + {}^{18}O)$ O is equal to 0.10 ± 0.04 in the detector. The mean mass of the stopping oxygen nuclei is 16.13 AMU.

The isotopic composition has been extrapolated to the top of the atmosphere by standard methods. The cross-sections have been derived from data in a paper by Silberberg and Tsao (1973), and from the measurements of nucleus-nucleus cross sections by Lindstrom et al. (1975).

The emulsion stack detector and the selection criteria accept stopping particles with a certain direction and a certain minimum residual range in the stack. The selection criteria are purely geometrical. Due to differences in the energy-range relations for different nuclides in the atmosphere and the stack these criteria for the detector accept different energy intervals for the different primary nuclides at the top of the atmosphere. Corrections have been applied both for differences in the width of the accepted energy interval and for the position of the interval on the energy scale.

We have calculated the effect of the solar modulation on the isotopic quotients. We have used the force field solution of the transport equation describing the cosmic ray modulation in a spherically symmetric region (Gleeson and Axford, 1968). When the modulation parameter ρ is given the value 0.7 GV, reasonable for 1970, the effect of the modulation on the isotope quotients turns out to be quite negligible.

The influence of the different effects described on the quotients is shown in Table II. The quotients in the last line are valid for near interstellar space. The quotients for ^{17}O and ^{18}O are 0.02 ± 0.02 and 0.07 ± 0.03, respectively. It is obvious that all corrections discussed in this section are small and their inherent uncertainty cannot influence the result noticeably.

In Table III we have compared our results with isotopic measurements of nitrogen and oxygen made by other groups. Only measurements above 50 MeV/nucleon have been included in Table III in order to exclude comparisons with solar particles or low energy cosmic ray data. The nitrogen data show that there is an appreciable amount of the heavier nitrogen isotope in the radiation. Most of the measurements made with a large variety of detector systems have given a ^{15}N/N ratio in the interval 0.3 - 0.6. Our result falls in the lower third of this interval. The mean value of the data presented in Table III is 0.47. This mean value must be taken with some reservation because of the possible existence of systematic errors.

The number of measurements of the isotopic composition of oxygen is at present small. Only two measurements apart from ours are included in Table III. The oxygen measurements show that ^{16}O is by far the most abundant oxygen isotope. The total abundance of ^{17}O and ^{18}O in the radiation in near interstellar space is about 10% of the total oxygen in the radiation.

5. Extrapolation to the source.

The isotopic composition of cosmic ray nitrogen and oxygen in near interstellar space depends on the composition of the radiation leaving the source and on transformations through nuclear reactions during the transport. Figure 5 will illustrate how the $^{15}N/N$ ratio depends on these factors. The ratio is computed as a function of the amount of matter traversed with the relative amount of nitrogen in the radiation near the source as a parameter. The calculations are made for an exponential vacuum path length distribution (E) and also on the assumption that all particles have traversed the same amount of matter (S). The exponential path length distribution is assumed to have neither a cut off nor a linear rise for small amounts of matter traversed. The C/O ratio is assumed to be equal to 1.00 near the source.

The calculations are made on the assumptions that the quotient $\frac{N}{CNO}$ is equal to 0.00, 0.05 and 0.10 in the radiation near the source. We have also assumed that all nitrogen in the source is ^{14}N. This assumption is in agreement with the isotopic composition of nitrogen in the solar system, which is $^{15}N/^{14}N = 0.0036$, and also with the composition of most other cosmic objects. The assumption means that a large fraction of the nitrogen in the source has not passed through the fast CNO-cycle, which, in equilibrium, gives a much higher $^{15}N/^{14}N$ ratio (Caughlan and Fowler, 1972). The assumption also excludes source matter which has been involved in processes connected to nova explosions possibly giving rise to large amounts of the most neutron rich stable nuclides (Hoyle and Clayton, 1974).

The nuclear cross-sections, which have been used in the extrapolation in Figure 5, have been computed with the formula given by Silberberg and Tsao (1973). We have assumed that all collisions have taken place with protons. On account of the general uncertainty in the cross-section values recently revealed by the new larger cross-sections measured by Lindstrom et al. (1975) we have also calculated the $^{15}N/N$ ratio with cross-sections, which have all been increased by 25%. The result of these calculations are shown by the dashed curves in Figure 5. The chang in the $^{15}N/N$ ratio due to this change is small, which implies that the ratio does not depend very sensitively on the general level of the cross-sections.

The $^{15}N/N$ ratio in Figure 5 has been computed on the assumption that the energy of the primary nuclei traversing interstellar matter amounted to 300 MeV/n. The energy dependence of this ratio was studied some years ago by Meneguzzi et al. (1971) and was found to be roughly constant in a very wide energy interval. On account of the new cross-sections, we have made a new calculation of the energy dependence of this ratio (Figure 6). The calculations are also in this case made for three source compositions N/CNO = 0.00, 0.05 and 0.10 respectively and with an exponential vacuum path length distribution with $\lambda = 6\ g/cm^2$.

Even with the new set of cross-sections the ratio is found to be insensitive to the energy. We also show in Figure 6 the experimental ^{15}N/N ratios given in Table III. The constancy of the calculated ^{15}N/N ratio justifies the calculation of a mean value of the experimental ratios, in spite of the different energies of the experiments.

Measurements of the chemical composition of the radiation have shown that the vacuum path length is about 6 g/cm^2 if an exponential vacuum path length distribution is assumed valid. If, instead, all particles have passed through the same amount of matter the slab thickness is estimated to 3-4 g/cm^2. Independently of which thickness of matter be accepted our experimental value ^{15}N/N = 0.34 ± 0.10 corresponds to a $\frac{N}{CNO}$ ratio in the source of 0.08 ± 0.03. If the mean value of all ^{15}N/N measurements (0.47) is used, one gets the source ratio $\frac{N}{CNO}$ = 0.04. The measurements of the isotopic composition of nitrogen thus support the assumption that nitrogen is present in the source. This result is in agreement with the results of measurements of the chemical composition of the radiation. Shapiro et al. (1975) report the quotient $\frac{N}{CNO}$ = 0.037 ± 0.009 in the source. This quotient is based upon a large number of charge composition measurements, an exponential vacuum path length distribution and cross-sections measured by Lindstrom et al. (1975). In a similar estimate by Meyer (1975) a N/O ratio between 0.04 and 0.08 is obtained and it is concluded that there is no significant indication of a depletion of nitrogen with respect to oxygen in galactic cosmic ray sources relative to solar system conditions.

Tsao et al. (1973) have calculated the change in the isotopic composition of oxygen during its traversal of interstellar matter. They found that above 2 GeV/n, cosmic ray oxygen can be expected to have a composition $^{16}O : ^{17}O : ^{18}O = 95.5:2.5:2.0$ in near interstellar space. The calculations were made on the assumptions that the oxygen in the source had the same isotopic composition as in the solar system and that the path length had the form $\exp(-0.24x)$, with a linear rise between 0 and 1 g/cm². Our experimental isotopic composition shows a somewhat higher ^{18}O-value than that expected from the calculations. The difference is, however, not statistically significant. The ^{18}O abundance reported by Fischer et al. (1976) seems to support an assumption that all ^{18}O nuclei are of secondary origin. On the other hand Beaujean et al. (1977) have reported a $(^{17}O + ^{18}O)/O$ quotient equal to 0.15 ± 0.02, which is difficult to explain as a result of interactions only.

6. Discussion.

One of the main problems in cosmic ray physics concerns the composition of the source matter and the physical processes which select the particles to be accelerated to high energy. According to one model the composition of cosmic rays is the same as that of the source matter just after the acceleration has started. The source matter is in this model enriched in heavy nuclei relative to the matter of the solar system. A recent development of this model assumes the cosmic ray matter to be selected directly from supernova remnant. This remnant is the ejected mantle of the exploded supernova thoroughly mixed with the supernova envelope and possibly with a certain amount of surrounding interstellar matter (Arnett and Schramm,1973; Hainebach et al., 1976).

In another type of model the cosmic ray source matter has a composition which is assumed to be approximately the same as that of the solar system. The difference between the composition of the radiation and the source is explained by a mechanism, which preferentially selects certain elements. According to one of these models the selection is made out of neutral matter by the ionization of the neutral atoms in collisions with fast electrons or protons (Kristiansson 1971, 1972, 1974). In another model the selection depends on the first ionization potential of the neutral atoms (Havnes 1971, 1973; Cassé and Goret 1973). The selection is in this case assumed to take place in an optically thin plasma at a moderate temperature (Cassé and Goret, 1978). In both of these models the atomic properties of the elements are thus of fundamental importance for the composition of the radiation.

In the following discussion we intend to compare the source abundance of nitrogen determined in the isotopic measurements with the nitrogen abundance expected for the different source models.

The supernova remnant model: A comparison was recently made by Hainebach et al. (1976) between the measured cosmic ray composition and the calculated composition of the ejected supernova remnant. A mixture of the supernova mantle and the surrounding envelope together with a certain amount of the interstellar medium was found to have a composition which showed great similarities with the cosmic radiation at the source. The comparison was, however, made with a cosmic ray composition which showed a much lower amount of nitrogen than that indicated by our isotope measurements. The difference between the nitrogen abundance is so large and of such importance that it is worth making a new comparison between the cosmic radiation and the remnant of the explosed supernova.

The ejected remnant is also in our comparison assumed to consist of the mantle of the evolved supernova and varying amounts of matter from the envelope and the surrounding interstellar matter. Both the envelope and the interstellar matter are initially assumed to have the comparison of the solar system . Table IV shows the abundances needed for the comparison. The cosmic ray data have been taken from the compilation by Shapiro et al. (1975). The nitrogen abundance is, however, deduced from our measurement of the isotopic composition $\left(\frac{N}{CNO} = 0.08\right)$. The abundances are given as mass fractions which is more convenient for the calculations. The abundances are given both above constant rigidity and above constant velocity. The fourth column shows the solar system composition also as mass fractions (Cameron, 1973). Columns 5, 6 and 7 list the composition of the evolved mantles of supernovae having mantle + core masses equal to 4 $M_\odot$, 8 $M_\odot$ and 16 $M_\odot$. The composition of the 4 $M_\odot$ and 8 $M_\odot$ mantle+core is taken from the paper by Hainebach et al. (1976), and the 16 $M_\odot$ mantle+core from Arnett and Schramm (1973). The initial total masses of the stars are 15 $M_\odot$, 22 $M_\odot$ and 36 $M_\odot$, respectively. The stars have, however, lost part of their envelopes during their evolution and the minimum mass for the remnant when producing cosmic radiation can therefore be appreciably less than the mass of the original star. The cosmic ray producing remnant can also be larger than the original star if it has swept up the matter evaporated from the star together with a certain amount of surrounding interstellar matter. Hainebach et al. (1976) have shown that the composition of the mantle of stars with the mantle+core mass larger than about 8 $M_\odot$ differs increasingly from the composition of the cosmic radiation. Such stars can therefore hardly be of importance as cosmic ray sources. This was the decisive reason for our abandoning the comparisons for mantle-core masses larger than 16 $M_\odot$.

In Figure 7 we show the calculated abundances of H, C, N, O, Ne and Mg relative to He in the remnant. The ratios are plotted as a function of the amount of envelope plus interstellar matter, which is swept up and completely mixed with the mantle. The ratios have been calculated from the expression

$$\left(\frac{Z}{He}\right)_{rem} = \frac{M(Z)_m + X_Z^{ism}\left(M_{env} + M_{ism}\right)}{M(He)_m + X_{He}^{ism}\left(M_{env} + M_{ism}\right)}$$

where

$\left(\frac{Z}{He}\right)_{rem}$ = the mass ratio between the element Z and He in the ejected remnant. The assumed complete mixing between the expelled mantle and a certain amount of the envelope and of interstellar matter makes the mass ratio the same in the whole remnant. How the mixing is brought about is not considered.

$M(Z)_m$ = the mass of the element Z in the mantle.

$M(He)_m$ = the mass of helium in the mantle.

X_Z^{ism} = the mass fraction of the element Z in interstellar matter (and in the envelope). It is assumed that no nuclear reactions take place in the envelope during the explosion.

X_{He}^{ism} = the mass fraction of helium in interstellar matter and in the envelope.

M_{env}, M_{ism} = the mass of envelope matter and interstellar matter with which the mantle has been mixed prior to the acceleration of the radiation.

In Figure 7 we also show the mass ratios for the cosmic radiation and for solar system matter by dashed horizontal lines marked by C.R. and S.S., respectively. The aim of Figure 7 is to compare the composition of the radiation with the composition of the remnant and if possible to find one mixture of mantle and solar system matter which gives a remnant with the same composition as the radiation. If matter from that remnant can be accelerated without any kind of preferential selection, the result will be a radiation having the composition of the cosmic radiation.

Figure 7 shows that the H/He-ratio does not depend in a sensitive way on the size of the supernova for mantle+core size in the interval 4-16 $M_\odot$. The ratio increases smoothly towards the solar system value when $M_{env} + M_{ism}$ increases. The H/He ratio has been compared with the composition of the radiation by Hainebach et al. (1976). Their results and our conclusions based on Figure 7 agree that the two ratios are equal when $M_{env} + M_{ism} \simeq 10\text{-}15\ M_\odot$ but only if the cosmic ray flux above constant rigidity C.R.(R) is chosen. If, instead, the H/He ratio is chosen for particles above the same velocity C.R.(β) the supernova remnant ratio never reaches the cosmic ray ratio.

It is thus possible to obtain the correct H/He ratio in the radiation only if there is a rigidity dependent selection working somewhere in the source. It is remarkable that this rigidity dependent selection mechanism does not seem to have any fluence on the abundance of the heavier nuclei. It must imply that if it is an electromagnetic process it is working only when the heavier nuclei have completely stripped off their electrons, making the charge to mass ratio approximately equal for all nuclei heavier than hydrogen.

The abundance ratios C/He, O/He, Ne/He and Mg/He can be used for an estimate of the approximate size of the supernovae possibly responsible for the radiation. Hainebach et al. (1976) have studied the abundances of He, C, Ne and Mg relative to O and found that a supernova having a mantle + core size of abou 4 $M_{\odot}$ has a composition of the remnant in best agreement with the radiation. Nearly the same conclusion can be drawn from the C/He, O/He, Ne/He and Mg/he ratios in Figure 7. These ratios indicate that the best size for the supernovae falls in the region 5-10 $M_{\odot}$ if the condition $M_{env} + M_{ism} \simeq 10\ M_{\odot}$ is fulfilled.

The supernova abundance ratios in Figure 7 are calculated for abundances in the evolved supernova. But changes in the composition of the mantle occur through nuclear reactions in the explosion. Hainebach et al. (1976) have studied the element synthesis in the explosive phase and found that the changes in the element abundances are comparatively small for a star having a mantle size of 5-10 $M_{\odot}$. This justifies our comparisons betwee element abundances for the evolved supernova instead of comparing abundances in exploded mantle matter.

In Figure 7 we also show how the N/He-ratio depends on $M_{env} + M_{ism}$. Nitrogen in the ejected remnant originates in the envelope and interstellar matter. No nitrogen comes from the ma This means that there will be a dilution of nitrogen when the supernova remnant is formed, and the nitrogen concentration in the remnant will be smaller than in interstellar matter. Cosmic radiation with the same composition as the supernova remnant would thus show a nitrogen abundance which is reduced relative to other heavy elements in the radiation and with a N/H source ratio which is the same as in interstellar matter.

The isotopic measurements of nitrogen presented in this paper support the assumption that nitrogen is present in the source to a degree which is higher than expected from the discussed theory of remnant origin. The two dashed lines in the N/He diagram show the value of the N/He source ratio when the N/CNO source ratio is 0.05 and 0.04, respectively. The $^{15}N/N$ ratio 0.34 ± 0.10 in the present investigation corresponds to the N/CNO ratio equal to 0.08 ± 0.03. This experimental value disagrees with the expected value for a remnant origin by about a factor 10 if $M_{env} + M_{ism} \simeq 10\ M_{\odot}$. The difference is so large that it seems difficult to accept a model with a cosmic ray composition similar to that assumed for the supernova remnant.

The disagreement between the model assumptions and the experimental results depends on the low abundance of nitrogen in the remnant. One must ask the question whether the nitrogen can be increased in the remnant. It seems completely impossible that a selection mechanism exists which increases only the amount of nitrogen in the radiation but leaves the abundances of all other elements unchanged. The nitrogen abundance can, however, be increased by nuclear reactions in the envelope before and during the supernova explosion. One obvious possibility is to assume that part of the envelope has been involved in a CNO-cycle either during the evolution of the star or in the explosion (Caughlan, 1965; Caughlan and Fowler, 1972). These processes may increase the nitrogen content in the remnant to the same level as in the radiation, without decreasing the C content so much that it can be observed in the comparison between cosmic ray abundance and remnant abundance. However, the production of ^{14}N in both the slow and the fast CNO-cycle must be proceeded by the production of nuclei with mass A = 13. We must accordingly expect a certain enhancement of ^{13}C in the radiation if the processes have taken place. Measurements of the isotopic composition of cosmic ray carbon have been reported from several groups. Thus, Bjarle et al. (1977) have obtained a ^{13}C/C ratio of 0.06 ± 0.03 at the top of the atmosphere. If this ratio is extrapolated to the source one gets the ratio ^{13}C/C = 0.0C ± 0.[illegible] (Tsao et al., 1973). Similar results are obtained by other groups and there is a general agreement that the ^{13}C/C quotient for the source is very low and approximately the same as in the matter of the solar system. There are thus no experimental cosmic ray carbon data which support the assumption that the CNO-cycle has been working in source matter. More specific conclusions require extensive calculations of the amount of ^{13}C, ^{14}N and ^{15}N, which can be produced in the supernova under different conditions.

The preferential selection models: In the other explanation of the composition of the radiation it is assumed that the source matter has a composition which is approximately the same as that of the solar system. The overabundance of certain elements in the radiation depends on a selection mechanism in the source region whose most characteristic feature is that the selection depends on the atomic properties of the elements. The selection mechanism according to Kristiansson (1971, 1974) is assumed to depend on the cross-section for the ionization of neutral atoms in collisions with fast charged particles. This model claims that

$$N(Z)_{C.R.} \sim \sigma(Z) \cdot N(Z)_S$$

where

$N(Z)_{C.R.}$ = the abundance of the element Z in the radiation.

$\sigma(Z)$ = the ionization cross-section.

$N(Z)_S$ = the abundance of the element Z in the source. It is assumed to be the same as in the solar system.

In Table V data relevant for the comparison with this model are assembled. Both the cosmic ray abundances and the solar system abundances are in this case given by numbers and normalized to 100 for carbon. The cosmic ray abundances are taken from Shapiro et al. (1975) with the exception of the nitrogen abundance, which is computed from our experimental $^{15}N/N$ ratio. For hydrogen both the number above a certain velocity (β) and above a certain rigidity (R) are given. The solar system abundances are taken from Cameron (1973). The ionization cross-sections are valid for collisions with electrons with an energy of 80 eV (Kristiansson, 1974).

The selection model states that the quotient $N(Z)_{C.R.}/(\sigma(Z) \cdot N(Z)_S)$ has to be the same for all elements. The fifth column in Table V shows that the quotients actually are about the same for all the elements including nitrogen. Our experimental nitrogen abundance is thus in agreement with this source mechanism. The quotient for hydrogen above constant velocity is also in agreement with the other quotients. It may indicate that the velocity is crucial in the selection. The quotient for neon seems to fall somewhat above the other quotients but the deviation is not unreasonably large in comparison with the uncertainty in the abundance used in the quotient.

In the source model by Havnes (1971) and Cassé and Goret (1978) the selection depends on the first ionization potential of the elements. The source matter is, in the model by Cassé and Goret (1978), a low density plasma with the elemental composition similar to the composition of the solar system, possibly moderately enriched with fresh products of nucleosynthesis from the time after the formation of the solar system. The plasma exists in ionization equilibrium and the plasma temperature varies through the plasma according to the relation $\rho(T) = \exp(-T/T_0)$ with $T_0 = 10^4$K. The abundance of an element in the cosmic radiation is in the first approximation assumed to be proportional to the abundance of that element and to the mean ionic fraction of the element in the whole plasma. The abundance of the element Z is accordingly

$$N(Z)_{C.R.} \sim \left(\frac{N_i}{N_{el}}\right)_Z \cdot N(Z)_S$$

where $(N_i/N_{el})_Z$ is the ionic fraction of the element Z i.e. the fraction of atoms which are ionized.

In the sixth column of Table V we show the ionic fraction normalized to the ionic fraction of silicon. The data have been taken from the paper by Cassé and Goret (1978). Finally in the last column of Table V we show a quotient which is supposed to be constant if the source model is correct. It is to be noticed that the quotient is approximately constant for all elements heavier than hydrogen. Our measured nitrogen abundance is thus in agreement also with this model. There is a remarkable deviation in the hydrogen value which means that this model requires a further selection mechanism which must be especially efficient for hydrogen in order to get the correct cosmic ray abundance. This selection has been extensively discussed by Cassé and Goret (1978).

Conclusion: As a conclusion of this paper we may state that our isotopic measurement of nitrogen supports the hypothesis that the radiation originates in a source having approximately the composition of the solar system and that a preferential selection mechanism, which depends on the atomic properties of the elements is working in the source when the cosmic ray nuclei are selected.

Acknowledgement.

The authors wish to thank Research Engineer Birgit Lindkvist for the processing of the plates and the Office of Naval Research, Washington D.C. for the balloon exposure. The support of the Swedish Natural Science Research Council is gratefully acknowledged.

Figure captions.

Fig. 1. The mass spectrum of nitrogen.

Fig. 2. The mass spectrum of oxygen. The curve is a Gaussian with $\sigma = 0.50$ AMU.

Fig. 3. The relation between track width W and restricted energy loss for ^{12}C and ^{16}O.

Fig. 4. The standard deviation in a mass measurement of oxygen as a function of measured track length.

Fig. 5. The ^{15}N/N ratio calculated as a function of the amount of interstellar matter passed. E = exponential path length model. S = slab model. The N/CNO ratio in the source is assumed to be 0.00, 0.05 and 0.10. The solid and the dashed curves are valid for different sets of cross-sections explained in the test. The calculation is made for an energy of 300 MeV/nucleon. Our experimental ^{15}N/N ratio is shown to the right of the computed curves.

Fig. 6. The ratio ^{15}N/N given as a function of energy for the N/CNO ratio in the source equal to 0.00 and 0.10. The circles represent the experimental measurements reported in Table III.

Fig. 7. Computed abundance quotients in supernova remnants. The ratios are plotted as a function of the amount of envelope plus interstellar matter in the remnant for stars with mantle plus core size of 4 $M_\odot$, 8 $M_\odot$ and 16 $M_\odot$. The dashed lines represent solar system composition (S.S.) and cosmic ray composition (C.R.) respectively.

TABLE I

The errors in the mass determinations

	Expected errors in the mass determination (AMU)	
	Nitrogen	Oxygen
Spread of measurements	0.41	0.43
9% excluded measurements	0.13	0.13
Error from corrections	0.11	0.11
Photometer fluctuations	0.14	0.20
Total error	0.46	0.50

TABLE II

The extrapolation of the mass quotients

	$\frac{^{15}N}{N}$	$\frac{^{17}O+^{18}O}{O}$
Measured in the stack	0.36	0.10
Corrected for nuclear reactions in the atmosphere	0.33	0.10
Corrected for the detector acceptance	0.34	0.10
Corrected for the modulation	0.34±0.10	0.10±0.04

TABLE III

Experimental mass ratios

		Detector Exposure	Energy MeV/n	$\frac{^{15}N}{N}$	$\frac{^{17}O}{O}$	$\frac{^{18}O}{O}$
aujean and 1972	a	Plastics, Balloon	~ 100	0.67±0.22		
ber et al. 973	b	Counter telescope, Balloon	~ 200	0.54±0,05		
ebber and Lezniak 974	c	Counter telescope, Balloon	750	0.28±9.19		
rcia-Munoz et al. 974	d	Counter telescope, Satellite	50-190	0.55±0.05		
yer and Meyer 975	e	Counter telescope, Balloon	1500	0.45±0.07		
isher et al. 976	f	Counter telescope, Balloon	350-600	0.4±0.2	≤ 0.065	0.025±0.015
agen et al. 977	g	Counter telescope, Balloon	250	0.57±0.08		
ujean et al. 977	h	Plastics, Balloon	100-200	0.40±0.09 0.47±0.09	$\frac{^{17}O+^{18}O}{O}$	* 0.15±0.02
his experiment	i	Emulsion Balloon	200-450	0.34±0.10	0.02±0.02	0.07±0.03

* From Meyer 1975.

TABLE IV

Element abundances used in the study of the supernova remnant model.

Element	Cosmic ray composition. Mass fraction		Solar system composition. Mass fraction	Mantle composition ($M_\odot$)		
	above constant rigidity	above constant velocity		4 $M_\odot$	8 $M_\odot$	10 $M_\odot$
H	0.57	0.754	0.768	-	-	
He	0.27	0.157	0.214	2.04	3.15	3.70
C	$3.2\cdot10^{-2}$	$1.81\cdot10^{-2}$	$3.43\cdot10^{-3}$	0.253	0.546	1.18
N	$0.67\cdot10^{-2}$	$0.38\cdot10^{-2}$	$1.23\cdot10^{-3}$	-	-	-
O	$4.5\cdot10^{-2}$	$2.58\cdot10^{-2}$	$8.29\cdot10^{-3}$	0.18	1.57	5.61
Ne	$8.4\cdot10^{-3}$	$4.8\cdot10^{-3}$	$1.68\cdot10^{-3}$	0.042	0.743	1.65
Mg	$1.5\cdot10^{-2}$	$8.3\cdot10^{-3}$	$6.23\cdot10^{-4}$	0.074	0.22	0.56

TABLE V

Element abundances used in the study of the preferential selection models.

Element	Cosm. ray abundance	Solar system abundance	Ionization cross-section (10^{-16} cm^2)	$\frac{N(Z)_{C.R.}}{\sigma(Z)\cdot N(Z)_S}$	$\left(\frac{N_i}{N_{el}}\right)_Z \Big/ \left(\frac{N_i}{N_{el}}\right)_{Si}$	$\frac{N(Z)_{C.R.}}{N(Z)_S\cdot\left(\frac{N_i}{N_{el}}\right)_Z \Big/ \left(\frac{N_i}{N_{el}}\right)_{Si}}$
H	$5\cdot10^4$ (β) $2\cdot10^4$ (R)	$2.69\cdot10^5$	0.65	0.29 0.11	0.44	0.42 0.17
He	2600	$1.87\cdot10^4$	0.36	0.39	0.059	2.4
C	100	100	2.25	0.44	0.60	1.7
N	18	32	1.54	0.37	0.36	1.6
O	111	182	1.67	0.37	0.44	1.4
Ne	15	29	0.62	0.83	0.13	3.9
Mg	24	9.0	4.8	0.56	0.95	2.8

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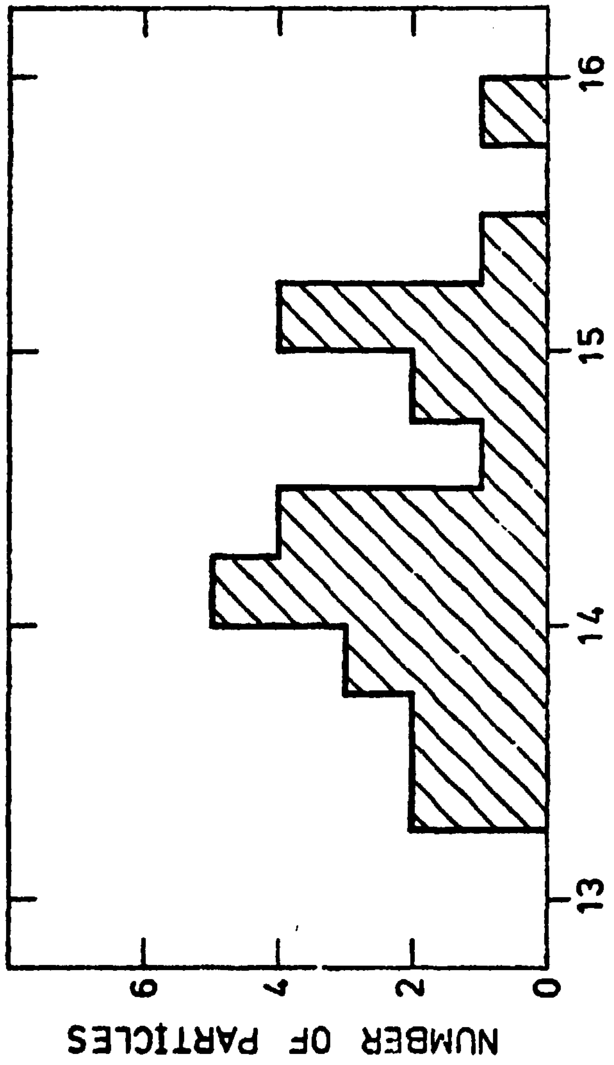
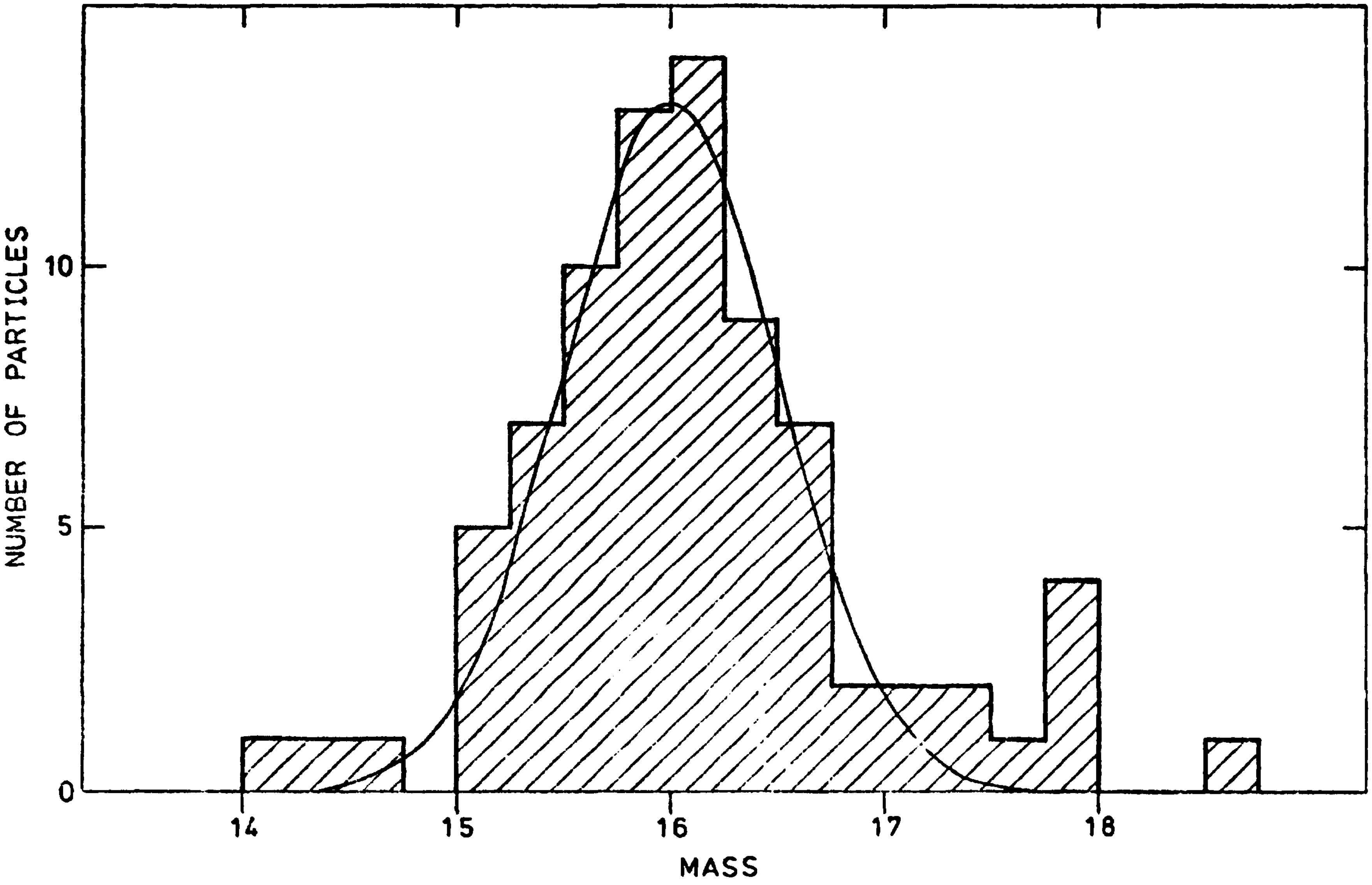


FIG. 1



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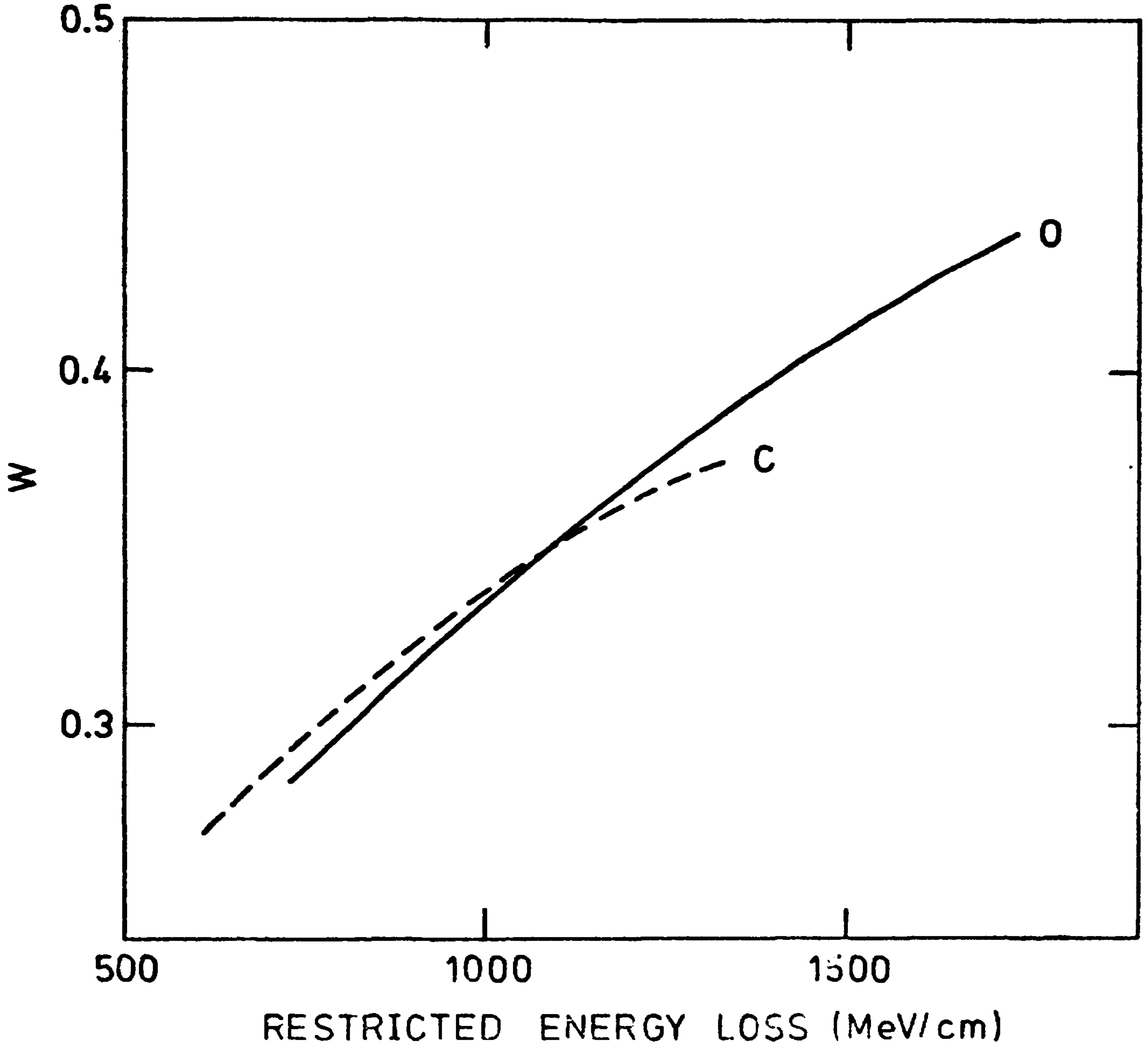

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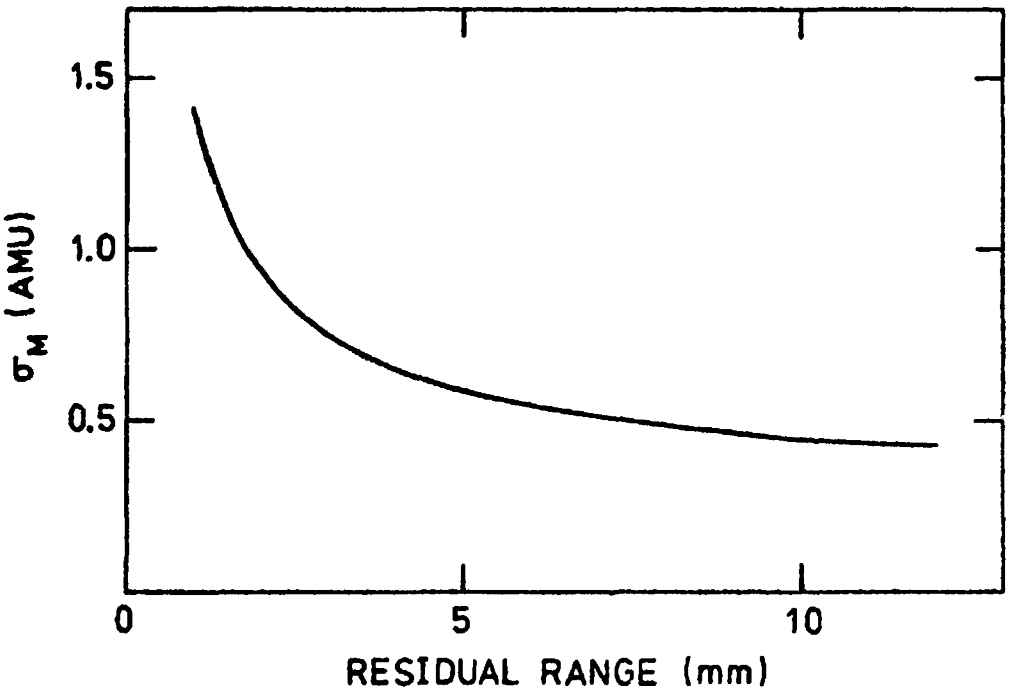

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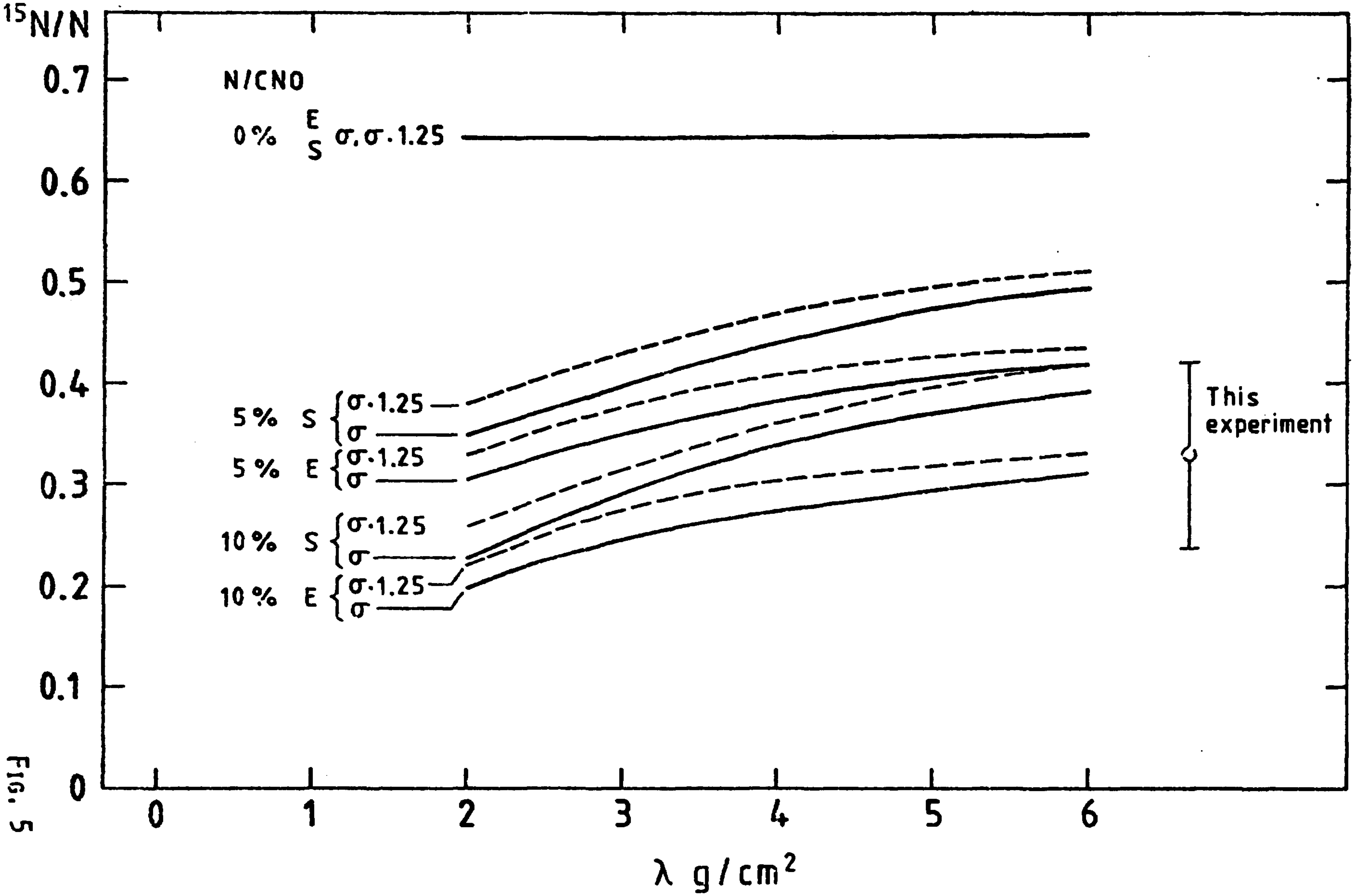
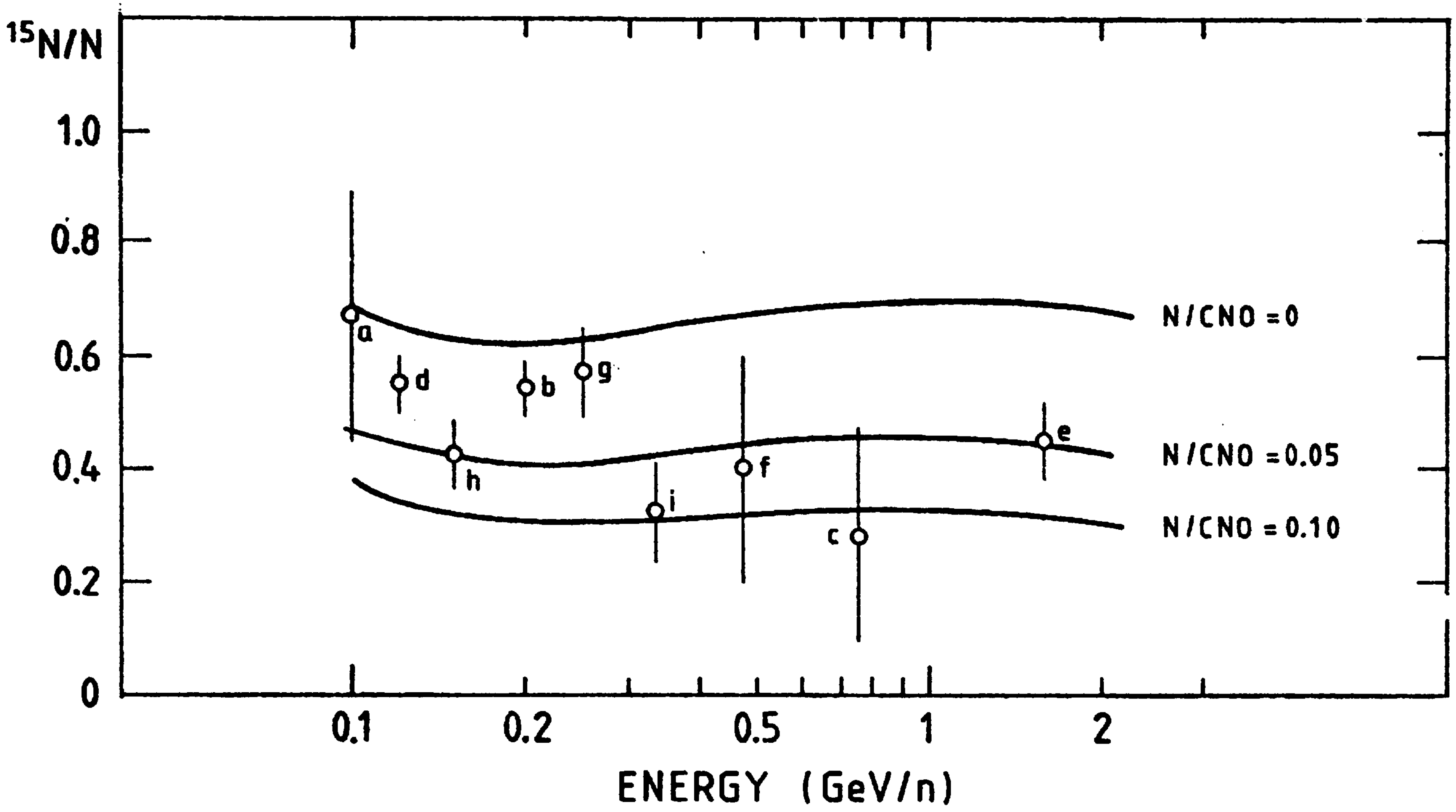

15N/N
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
N/CNO
0 % E S σ, σ·1.25
5 % S σ·1.25
σ
5 % E σ·1.25
σ
10 % S σ·1.25
σ
10 % E σ·1.25
σ
This experiment
0
1
2
3
4
5
6
λ g/cm²

FIG. 5



$^{15}N/N$
1.0
0.8
0.6
0.4
0.2
0
0.1
0.2
0.5
1
2
ENERGY (GeV/n)
a
b
c
d
e
f
g
h
i
N/CNO = 0
N/CNO = 0.05
N/CNO = 0.10

FIG. 6

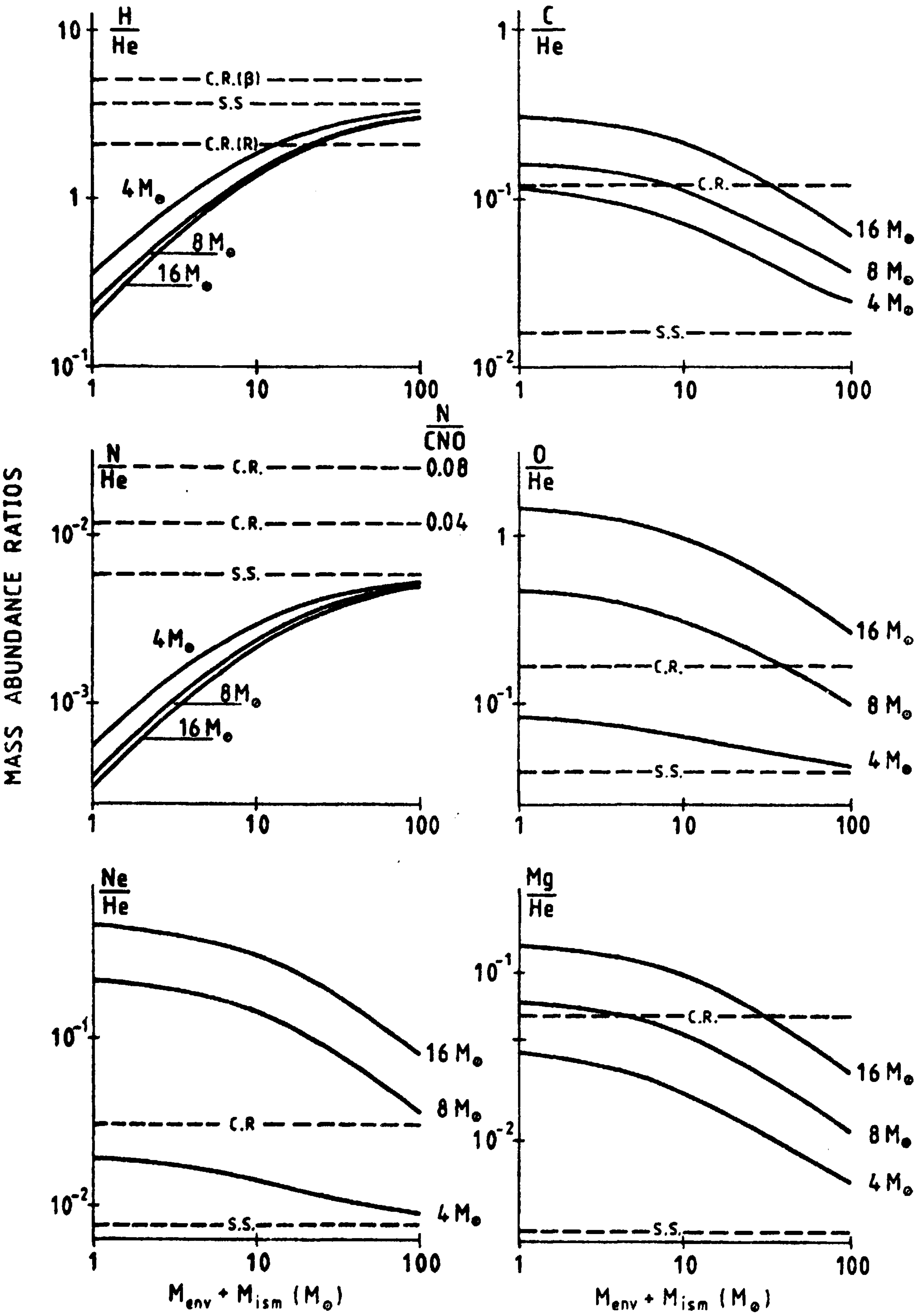

MASS ABUNDANCE RATIOS
H/He
10
1
10^-1
C.R.(β)
S.S
C.R.(R)
4 M☉
8 M☉
16 M☉
C/He
1
10^-1
10^-2
C.R.
S.S.
16 M☉
8 M☉
4 M☉
N/He
N/CNO
C.R.
0.08
C.R.
0.04
10^-2
S.S.
4 M☉
10^-3
8 M☉
16 M☉
O/He
1
16 M☉
C.R.
10^-1
8 M☉
4 M☉
S.S.
Ne/He
10^-1
16 M☉
8 M☉
C.R
10^-2
4 M☉
S.S.
Mg/He
10^-1
C.R.
16 M☉
8 M☉
10^-2
4 M☉
S.S.
1
10
100
Menv + Mism (M☉)

FIG. 7

Dokumentutgivare
UNIVERSITY OF LUND
Handläggare
Department of Physics

Författare
L Jacobsson
G Jönsson
K Kristiansson

Dokumentnamn
Internal report
Utgivningsdatum
1978-12-07

Dokumentbeteckning
LUNFD6/(NFFK-7011)
Ärendebeteckning

Dokumenttitel och undertitel

Isotopic composition of primary cosmic ray nitrogen and oxygen with consequences for source models.

Referat (sammandrag)

An experimental investigation of the isotopic composition of cosmic ray nitrogen and oxygen is reported. The detector is a stack of nuclear emulsions exposed at about 3 g/cm^2 atmospheric depth. The mass determinations are based on photometric track width measurements on stopping nuclei. The standard deviation of the mass measurements is 0.46 AMU for nitrogen and 0.50 AMU for oxygen. The energy of the measured nuclei falls in the interval 220-450 MeV/nucleon at the top of the atmosphere.

The measured isotopic quotients have been extrapolated to near interstellar space with standard methods. The extrapolated quotients are $^{15}N/N = 0.34 \pm 0.10$, $^{17}O/O = 0.02 \pm 0.03$, $^{18}O/O = 0.07 \pm 0.03$. The nitrogen quotient extrapolated to the cosmic ray source shows that the nitrogen-oxygen abundance ratio is approximately the same in the source as in the solar system. The result has been compared with different hypotheses about the source composition and is found to be in best agreement with a hypothesis, which states that source matter has approximately the composition of the solar system and that a selection mechanism depending on the atomic properties of the elements is working in the source.

Referat skrivet av
The authors.

Förslag till ytterligare nyckelord

Klassifikationssystem och -klass(er)

Indextermer (ange källa)

Omfång 36 pages,
7 figures, 5 tables.

Övriga bibliografiska uppgifter

Språk English

Sekretessuppgifter

ISSN

ISBN

Dokumentet kan erhållas från
Department of Cosmic and Subatomic Physics
University of Lund, Sölvegatan 14
S-223 62 LUND, Sweden.

Mottagarens uppgifter

Pris

Blankett LU 11:25 1976-07