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AUTHOR(S): Robert C. Reedy

SUBMITTED TO: Proceedings of the 15th Lunar and Planetary Science Conference.

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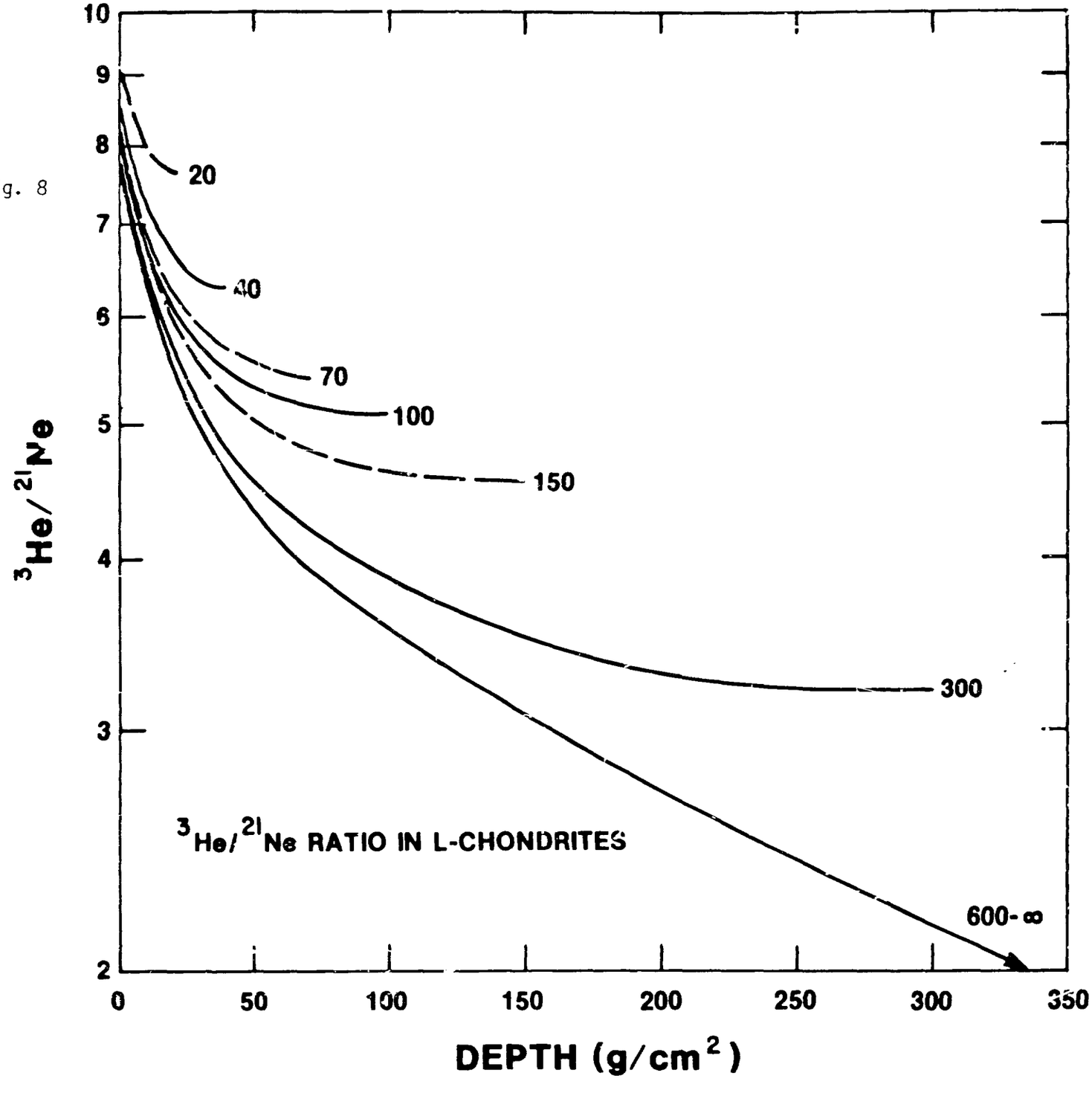
Fig. 8


$^3He/^{21}Ne$
DEPTH (g/cm^2)
$^3He/^{21}Ne$ RATIO IN L-CHONDRITES
20
40
70
100
150
300
600-∞
10
9
8
7
6
5
4
3
2
0
50
100
150
200
250
300
350

A Model for GCR-Particle Fluxes in Stony Meteorites and Production Rates of Cosmogenic Nuclides

R. C. Reedy

Los Alamos National Laboratory and Max-Planck-Institut für Chemie, Mainz, FRG

Short title: GCR-Particle Fluxes and Cosmogenic Nuclides in Meteorites

Abstract

A model is presented for the differential fluxes of galactic-cosmic-ray (GCR) particles with energies above 1 MeV inside any spherical stony meteorite as a function of the meteorite's radius and the sample's depth. This model is based on the Reedy-Arnold equations for the energy-dependent fluxes of GCR particles in the moon and is an extension of flux parameters that were derived for several meteorites of various sizes. This flux model is used to calculate the production rates of many cosmogenic nuclides as a function of radius and depth. The peak production rates for most nuclides made by the reactions of energetic GCR particles occur near the centers of meteorites with radii of 40 to 70 g cm^{-2}. Although the model has some limitations, it reproduces well the basic trends for the depth-dependent production of cosmogenic nuclides in stony meteorites of various radii. These production profiles agree fairly well with measurements of cosmogenic nuclides in meteorites. Some of these production profiles are different than those calculated by others. The chemical dependence of the production rates for several nuclides varies with size and depth.

Introduction

The production rates of cosmic-ray-produced nuclides in meteoritic samples vary with the meteorite's size and shape and with the sample's location. These changes in the production rates as a function of a sample's shielding condition result from the variations of the fluxes of primary and secondary cosmic-ray particles inside a meteorite. As the primary particles

in the cosmic rays penetrate a meteorite, they are removed and secondary particles, especially neutrons, are produced and are subsequently removed. Both the flux of cosmic-ray particles and the energy spectral shape of these particles change inside a meteorite. Cosmogenic nuclides are made by primary and secondary particles with energies that are determined by the nuclear reactions producing a nuclide.

Many investigations of the variations of the cosmic-ray flux or of the history of a meteorite's cosmic-ray exposure require good shielding-dependent production rates [Reedy et al., 1983]. For example, the irradiation histories of Shergotty, Nakhla, Chassigny, and other SNC meteorites are important in establishing whether these objects came from Mars and, if so, when and how they were ejected [Bogard et al., 1984]. Reported here is a model for the fluxes of primary and secondary galactic-cosmic-ray (GCR) particles as a function of depth in spherical meteorites of any radius. These fluxes are used to calculate the production rates of several cosmogenic nuclides in L-chondrites. This model can be used to calculate the production rates of many nuclides in stony meteoritic samples of any chemical composition. The production of nuclides by the solar cosmic rays (SCR) is not considered here because the surface layers where SCR effects are important are usually removed by ablation when a meteorite passes through the earth's atmosphere; however, SCR-produced nuclides are probably present in certain meteoritic samples [Michel et al., 1982].

The variations in the concentrations of cosmogenic nuclides in a meteorite were first studied in detail in the slabs of several large iron meteorites. Signer and Nier [1960] used their measurements for the cosmogenic

noble gases in the iron meteorite Grant to obtain a semi-empirical model for nuclide production as a function of radius and depth. Arnold et al. [1961] estimated the differential energy spectra of cosmic-ray particles for two different depths in iron meteorites and calculated the production rates of cosmogenic nuclides by using cross sections for the main reactions. Kohman and Bender [1967] used the measured distributions of radionuclides in thick targets of iron bombarded by beams of high-energy protons to model radius- and depth-dependent production rates.

The variations in the production rates and ratios of cosmogenic nuclides were first investigated in stony meteorites by comparing various production rates or ratios measured for a number of different meteorites. For example, the $^{3}He/^{21}Ne$ and $^{22}Ne/^{21}Ne$ ratios in many stones varied, but the $^{3}He/^{21}Ne$ ratios showed a systematic trend with the $^{22}Ne/^{21}Ne$ ratios; most fell near a correlation line [Eberhardt et al., 1966]. The isotope ratio $^{22}Ne/^{21}Ne$ has been used for empirically determined shielding-corrected production rates [for example, Nishiizumi et al., 1980], but this ratio does not uniquely determine the sample's exact exposure geometry or a nuclide's production rate. Some production rates in stony meteorites were calculated as a function of size and depth by Trivedi and Goel [1973] using thick-target results for silicate targets and the model of Kohman and Bender [1967] but only for the radionuclides ^{3}H and ^{22}Na. Nyquist [1984] has extended the semi-empirical model of Signer and Nier [1960] to chondrites for several noble-gas isotopes.

Reedy and Arnold [1972] applied the flux and cross-section approach of Arnold et al. [1961] to the moon and derived a new expression for the flux of GCR particles with energies below 100 MeV. The depth-dependent variations of

cosmogenic nuclides in meteorites have been studied by measuring samples with documented locations from cores (such as Keyes and St. Severin) or large fragments (for example, Jilin) of a meteorite. These activity-versus-depth results have been used by Reedy et al. [1978, 1979] and Bhattacharya et al. [1980] to determine specific sets of flux parameters for these meteorites. The equations for the GCR-particle spectra that were used for these meteorite models are the lunar ones of Reedy and Arnold [1972]. The model reported here generalizes these and other flux-parameter sets for several meteorites to get expressions for the depth-dependent GCR flux in meteorites of any radius.

Model for GCR-Particle Fluxes in Meteorites

This new meteorite GCR-particle flux model is based on the model developed by Reedy and Arnold [1972] for the moon. The Reedy-Arnold model uses two variables: a flux normalization and a spectral-hardness parameter, α. For spherical stony meteorites, the flux normalization is calculated using the interaction and other parameters of Reedy and Arnold [1972] and an omnidirectional integral flux above 1 GeV of 1.87 protons cm^{-2} s^{-1} [Reedy et al., 1979]. This flux is 10% higher than that used by Reedy and Arnold [1972] for 1 AU but is only 4% higher than a more recent estimate [Reedy, 1983] of the average GCR proton integral flux above 1 GeV at 1 AU. The flux of GCR particles to which a meteorite is exposed should be a little higher than that at 1 AU because the flux increases with distance from the sun at the rate of about 2 to 3% per AU [for example, McKibben et al., 1982] and meteorites probably receive most of their cosmic-ray exposure at 2 to 3 AU from the sun. These fluxes are the average over an 11-year solar cycle; the actual

GCR-particle flux above 1 GeV nucleon^{-1} near 1 AU varies by a factor of about two over a solar cycle [Reedy, 1983].

The integral fluxes of GCR particles with energies above 1 GeV nucleon^{-1} that were calculated as a function of depth in meteorites of various radii are shown in Figure 1. The shapes of these fluxes versus depth curves show the effects of an omnidirectional source of primary GCR particles. The fluxes of GCR-particles inside meteorites change slowly near the centers of spherical meteorites and vary most rapidly near the surface. Even for fairly large meteorites, these fluxes are considerably above those for the same depth in a semi-infinite slab (an infinite radius).

The model of Arnold et al. [1961] used the expression $(E + \alpha)^{-2.5}$ for the GCR-particle spectral shape above 100 MeV. The model of Reedy and Arnold [1972] kept this spectral expression above 100 MeV, but it had new equations for the differential flux of GCR-particles with energies below 100 MeV that changed shape as the spectral-hardness parameter α changed. The Reedy and Arnold [1972] expressions for the fluxes of GCR-particles as a function of energy were used for meteorites by Reedy et al. [1978, 1979] and Bhattacharya et al. [1980]. For the meteorites studied by these investigators, curves of α versus depth were derived to fit the cosmogenic-nuclide measurements. However, only a few specific sets of α curves were derived, and no generalizations or expressions for spectral hardness were developed for other meteorites.

An expression for the spectral-hardness parameter as a function of meteorite radius R and sample depth d, $\alpha(R,d)$, has been developed by fitting four cases: R = 0, 70, and 300 g cm^{-2}, and an infinite radius. A value of

α = 944 MeV gives a very crude approximation to the primary GCR spectrum (or R = 0). The α curve for St. Severin [Reedy et al., 1979] was used for R = 70 g cm^{-2}. The lunar α curve [Reedy and Arnold, 1972] was used for an infinite radius. The α curve for R = 300 g cm^{-2} was determined by fitting the ^{22}Na activities measured for depths of 15 to 50 cm in Jilin (which was formerly called Kirin) [Heusser and Ouyang, 1981; G. Heusser, personal communication, 1982]. The ^{22}Na activities in Jilin are fairly constant for these depths, unlike the predictions of Trivedi and Goel [1973], which show a strong drop with increasing depth for a meteorite of that radius. The α versus depth curves for these four cases are fairly well determined. Using these four curves, a relation was derived that fits these radii and that can be used for other radii.

The generalized equation for $\alpha(R,d)$ is

$$\alpha(R,d) = f(R)*\alpha_{RA}(d) + b(R)*\alpha_{RA}(2R-d),$$

where $\alpha_{RA}(x)$ is the Reedy and Arnold [1972] value of α at a depth x in the moon, and f(R) and b(R) are parameters representing particles coming from the front and back of a meteorite of radius R. For x > 80 g cm-2, $\alpha_{RA}(x)$ = 324.44*exp(-0.004838x). The original α curve of Reedy and Arnold [1972] only had this shape for 80 < x < 350 g cm^{-2} and approached a constant value of α = 50 MeV at a depth of 500 g cm^{-2}. Data for cosmogenic nuclides deep in the moon and in Jilin suggest that α should continue to decrease roughly exponentially below 350 g cm^{-2}. The parameter f(R) is 0.78 for R < 64 g cm^{-2} and 1 - exp(-0.0085R - 0.97) for larger radii, and b(R) is 0.73 for R < 40 g cm^{-2}

and 0.65 + 0.002R for greater radii. For very large radii, $\alpha(R,d)$ is assumed to be the same as $\alpha_{RA}(d)$.

Several spectral-hardness curves calculated with the above expression are shown in Figure 2. The α versus depth curves for R = 70 and 300 g cm^{-2} reproduce very well the original curves derived for St. Severin and Jilin. When compared to the curves in Bhattacharya et al. [1980], these $\alpha(R,d)$ values are all similar in shape but are higher than their values for R of 15 cm and greater. As in the case of flux normalization curves in Figure 1, these curves for α as a function of depth are fairly constant near the centers of spherical meteorites. The α profiles for radii above about 600 g cm^{-2} are very nearly that for a slab. Because the largest meteorite used in obtaining these curves had a radius of 300 g cm^{-2}, there could be some uncertainties in these α versus depth curves for very large radii. However, the absolute flux of particles, not the spectral shape, controls the production of cosmogenic nuclides in very large meteorites.

Calculated Production Rates

Calculated production rates for several cosmogenic nuclides as a function of depth in spherical L-chondrites of various radii are shown in Figures 3 - 7. For ^{26}Al, the cross sections of Reedy and Arnold [1972] were used. For ^{10}Be, new cross sections were used that give good fits to experimental profiles in cores from St. Severin and the moon [Tuniz et al., 1984]. Cross sections for the production of the light noble-gas isotopes of ^{3}He, ^{21}Ne, and ^{38}Ar were from Reedy [1981], Reedy et al. [1979] and Hohenberg et al. [1978],

respectively. The rates for ^{3}He have been multiplied by a factor of 1.4 to get the proper ^{3}He production rates [Reedy et al., 1978; Reedy, 1981]. The profiles in these figures show the effects of the build-up of secondary neutrons and the attenuation of primary and, eventually, secondary particles. These calculations reproduce fairly well the measurements of cosmogenic nuclides in meteoritic samples. The shapes of these production profiles are qualitatively similar to those of previous calculations, but there are some significant differences.

The ^{21}Ne production profile calculated here for R = 70 g cm^{-2} is the same as that in Reedy et al. [1979], which gave a fairly good fit to the measured data ^{21}Ne for St. Severin [Schultz and Signer, 1976]. The calculated profile for ^{53}Mn in St. Severin had the same shape as that measured by Englert and Herr [1980]. The calculated and measured ^{10}Be profiles in St. Severin agreed fairly well [Tuniz et al., 1984]. The only test for a meteorite with a radius of 300 g cm^{-2} is to use ^{22}Na for depths of about 50 to 185 g cm^{-2} in Jilin [G. Heusser, personal communication, 1982]. The calculated production profile for ^{22}Na is similar to those of ^{26}Al and ^{38}Ar, and the activity of ^{22}Na should drop near the center of Jilin. Samples from the center of Jilin were recently obtained [Heusser et al., 1983] and ^{22}Na measurements are being made, which will provide an additional test of this model for large meteorites.

The calculated production profiles for ^{3}H and ^{22}Na are similar to those of Trivedi and Goel [1973] for R < 100 g cm^{-2}, but for larger radii the profiles calculated here drop much slower with increasing depth than do theirs. The Trivedi and Goel [1973] profile for ^{22}Na gives a very poor fit to the ^{22}Na measured in Jilin [G. Heusser, personal communication, 1982]. The Trivedi-Goel profile for ^{3}H in a meteorite of infinite radius decreases with

depth at twice the rate calculated here and by Reedy and Arnold [1972]. Nyquist [1984] compared the results for ^{3}He and ^{21}Ne in chondrites from his semi-empirical model with those for this model. The basic trends are similar, but there are some minor differences. For example, Nyquist's model doesn't have an increase for ^{3}He production with depth near the surface, but such an ^{3}He increase with depth was observed for St. Severin [Schultz and Signer, 1976].

The calculated ratios of $^{3}He/^{21}Ne$ as a function of radius and depth are shown in Figure 8. Most of the $^{3}He/^{21}Ne$ ratios measured for meteorites are between 3 and 8, which is the region of Figure 8 that corresponds to typical meteoroid radii The calculated curves of $^{3}He/^{21}Ne$ versus $^{22}Ne/^{21}Ne$ for different radii all fall along a single line, whereas the results for this ratio in meteoritic cores plot as a line [for example, Schultz and Signer, 1976], but at a slight angle to the Eberhardt et al. [1966] trend line. Some of this deviation in the core data from the trend line could be due to SCR-production, but most of the divergence is probably real. Any model like the present one with just one parameter for the spectral shape will only give a single line for the $^{3}He/^{21}Ne$-versus-$^{22}Ne/^{21}Ne$ plot for different radii. The fact that the core data do not deviate much from the main trend line indicates that the present model is not a bad approximation. Plots for many radii of the calculated $^{22}Ne/^{21}Ne$ ratio versus a calculated production rate look similar to those of Nishiizumi et al. [1980] for $R < 200$ g cm^{-2}, but for larger radii almost any production rate is possible for the smallest values of the $^{22}Ne/^{21}Ne$ ratio.

In Figures 3 to 7, the points plotted for pure GCR primary protons were calculated with the spectrum of Reedy [1983] and are about 0.5 of those calculated with $\alpha(C,O)$. This model is probably not very accurate for $R < 20$ g cm^{-2} because it most likely overestimates the number of secondary neutrons. For such small objects, a significant fraction of the low-energy particles are protons, whereas this model, like that of Reedy and Arnold [1972], assumes that the low-energy particles are predominately neutrons. A model that explicitly considers neutrons and protons and their corresponding cross sections separately is needed for such small meteorites. I also suspected that the radii for this model really refer to meteoroid radii that are about 5 g cm^{-2} greater than the nominal value of R.

Discussion

The model presented here for the fluxes of GCR particles in meteorites is a generalization of previous results for several meteorites. It can be used to calculate the production rates of a variey of cosmogenic nuclides in samples at any depth in spherical stony meteorites of different radii. The use of the spectral model of Reedy and Arnold [1972], which has only one free shape parameter, is probably too simple an approach, but it does give reasonable production rates for a range of radii. For most meteorites, which have radii between about 40 and 300 g cm^{-2}, this model is fairly good. It most likely is not very good for smaller meteorites. The flux normalization, which controls the production rates of cosmogenic nuclides more than does the spectral-hardness parameter, is relatively good for larger radii.

Calculations for the production rates of cosmogenic nuclides in stony meteorites agree fairly well with measurements. Unfortunately, only several cosmogenic nuclides measured in the cores or main masses of just a few meteorites were used in deriving this model; additional measurements for documented locations in other meteorites are needed to verify and refine this model. The calculated production rates agreed fairly well with other calculations, but several major discrepancies exist. For most of the disagreements among the predictions of these models, the results of the present calculations agree better with measurements.

This model was used by Reedy [1984] to calculate the production rates of cosmogenic noble gases in six different SNC meteorites. The production rates of ^{21}Ne and ^{38}Ar varied widely among these achondrites because of their very different chemistries. For these and some other nuclides in several of these SNC meteorites, the production rates relative to that for the same exposure geometry in an L-chondrite varied with sample depth and was not just a function of chemistry only. These depth-dependent ratios for different chemistries result when a product is made by at least two reactions, one of which is induced by GCR particles with energies considerably different than those inducing the other reactions. For example, the production profile of ^{38}Ar from calcium (involving mainly low-energy particles) is different than that of ^{38}Ar from iron (a high-energy reaction). The ratio of ^{38}Ar production from calcium to that from iron can increase by a factor of two from the surface to the center of a large meteorite.

These rates for production of spallogenic nuclides by GCR particles as a function of depth and radius are probably a fairly good representation of the

true systematics in spherical stony meteorites. They change most rapidly at the surface and approach a constant production rate in the centers of spherical meteorites. These production rates cover a wide range of values over the possible meteorite radii and sample depths. They are not simply twice the value for a slab geometry. Using only spallogenic nuclides, it is very hard to determine uniquely where a sample was irradiated and the size of the meteorite. However, ratios like $^{3}He/^{21}Ne$ can be used in many cases to restrict the range of possible production rates for a cosmogenic nuclide. To best unfold the exposure history of a meteorite, measurements of many different products that are made by the cosmic rays with a variety of production profiles are needed for several samples from known locations. Such extensive sets of measurements will not only improve our understanding of the production systematics of cosmogenic nuclides, but will also help define possible cosmic-ray variations and determine the origin and evolution of meteorites.

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R. C. Reedy, Nuclear Chemistry Group, MS-J514, Los Alamos National Laboratory, Los Alamos, NM 87545.

FIGURE CAPTIONS

Fig. 1. The calculated fluxes of GCR particles with energies above 1 GeV nucleon^{-1} as a function of depth for meteorites of various radii. The x is the omnidirectional incident flux of primary GCR particles in space to which the meteorites were assumed to be exposed.

Fig. 2. The spectral-hardness parameter $\alpha(R,d)$ as a function of sample depth for several meteoroid radii (in g cm^{-2}). The values of α for the centers of meteorites with intermediate radii are indicated with x.

Fig. 3. Calculated production rates of ^{26}Al as a function of depth in L-chondrites of several radii. The radii are in g cm^{-2} and an infinite radius corresponds to a semi-infinite plane or a slab. The x marks the production rates for pure GCR primary protons calculated with the average primary GCR-proton spectrum of Reedy [1983].

Fig. 4. Calculated production rates versus depth for ^{10}Be in L-chondrites. See caption for Figure 3 for more details.

Fig. 5. Calculated production rates versus depth for ^{3}He in L-chondrites. See caption for Figure 3 for more details.

Fig. 6. Calculated production rates versus depth for ^{21}Ne in L-chondrites. See caption for Figure 3 for more details.

Fig. 7. Calculated production rates versus depth for ^{38}Ar in L-chondrites. See caption for Figure 3 for more details.

Fig. 8. The calculated $^{3}He/^{21}Ne$ ratio as a function of depth in L-chondrites of various radii. A ratio of 16.3 was calculated for the primary GCR protons using the spectrum of Reedy [1983].

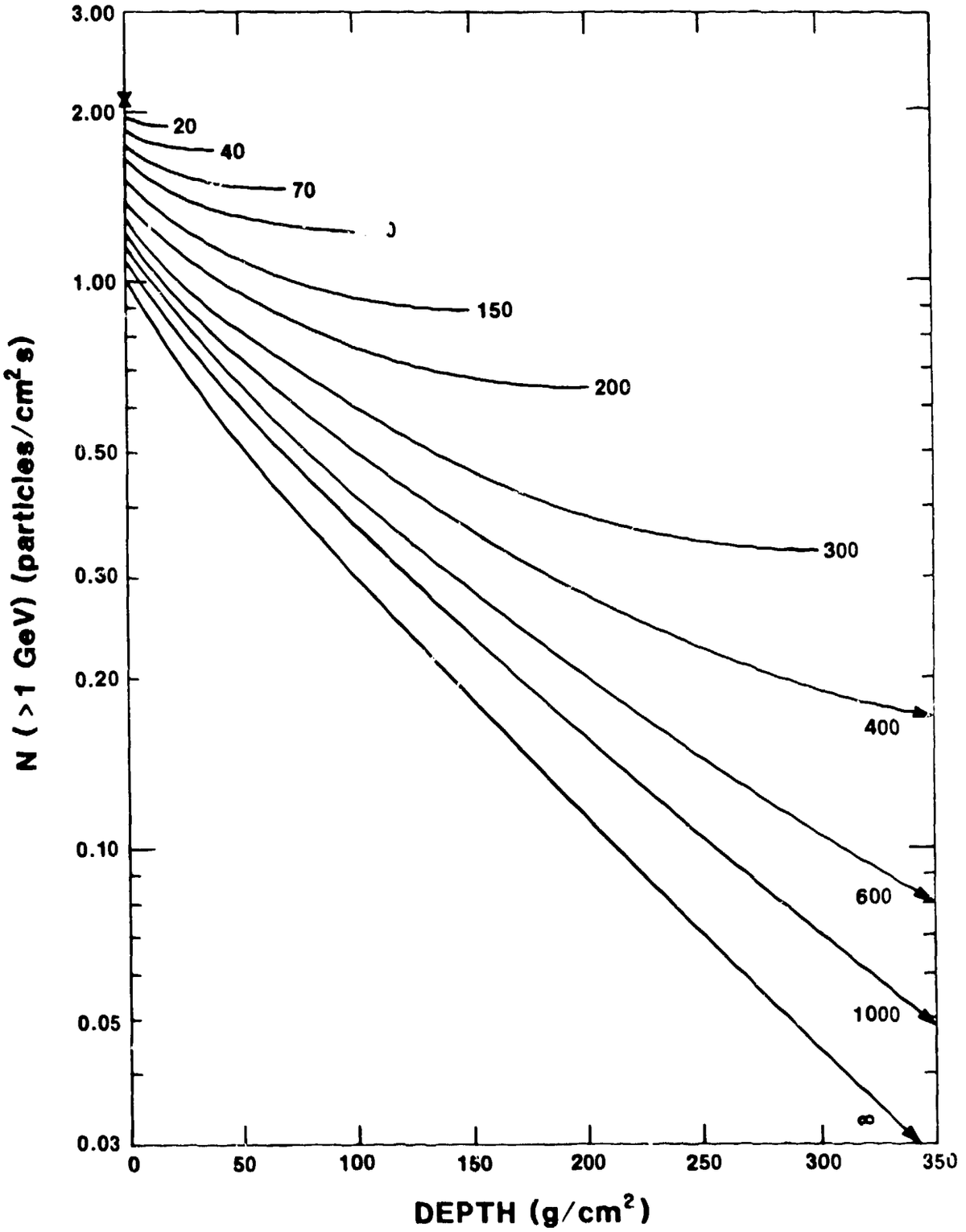

3.00
2.00
1.00
0.50
0.30
0.20
0.10
0.05
0.03
N (>1 GeV) (particles/cm²s)
20
40
70
150
200
300
400
600
1000
∞
0
50
100
150
200
250
300
350
DEPTH (g/cm²)

Fig. 1

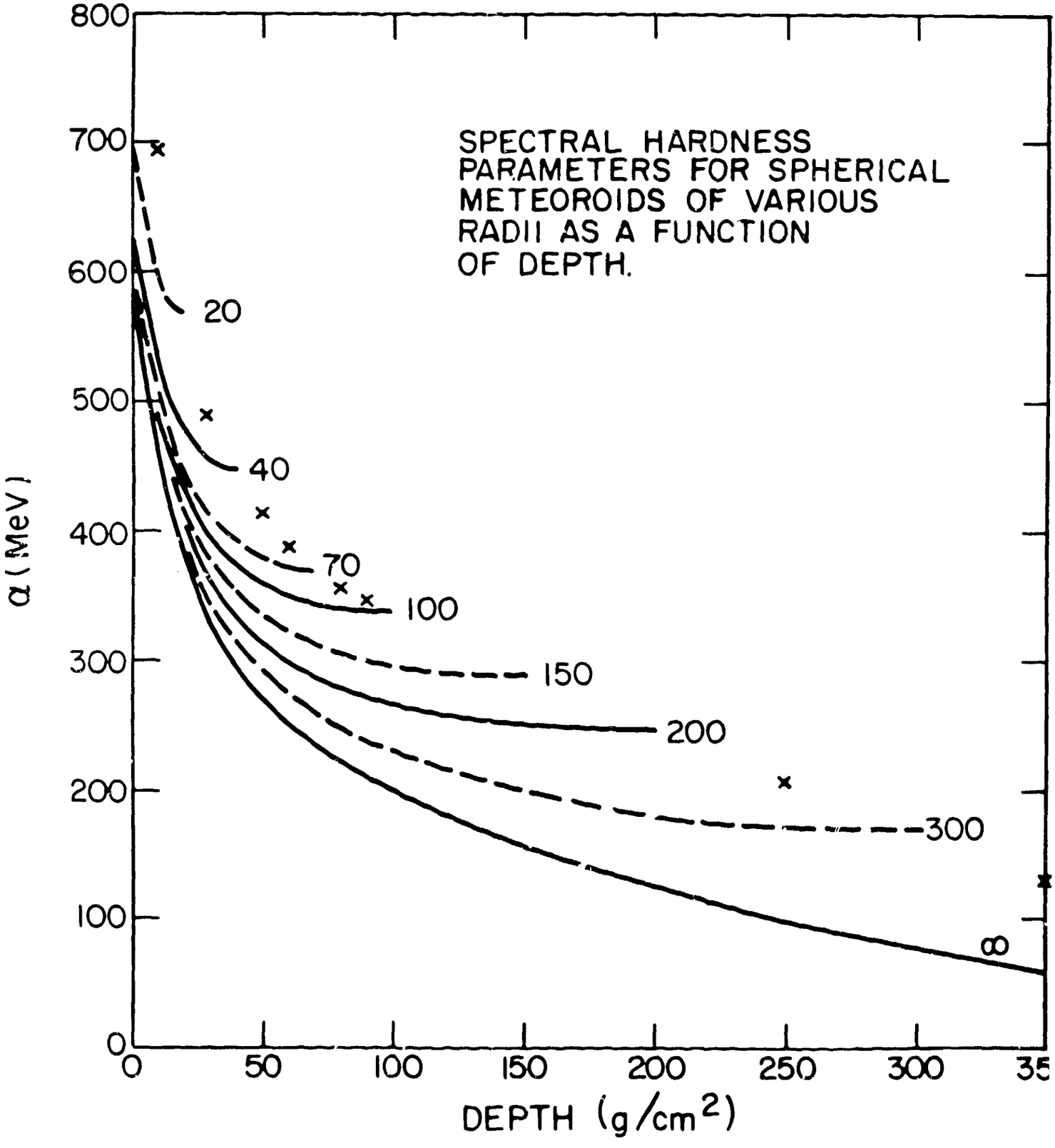

SPECTRAL HARDNESS
PARAMETERS FOR SPHERICAL
METEOROIDS OF VARIOUS
RADII AS A FUNCTION
OF DEPTH.
α (MeV)
DEPTH (g/cm²)
0
100
200
300
400
500
600
700
800
50
150
250
20
40
70
100
150
200
300
∞

Fig. 2

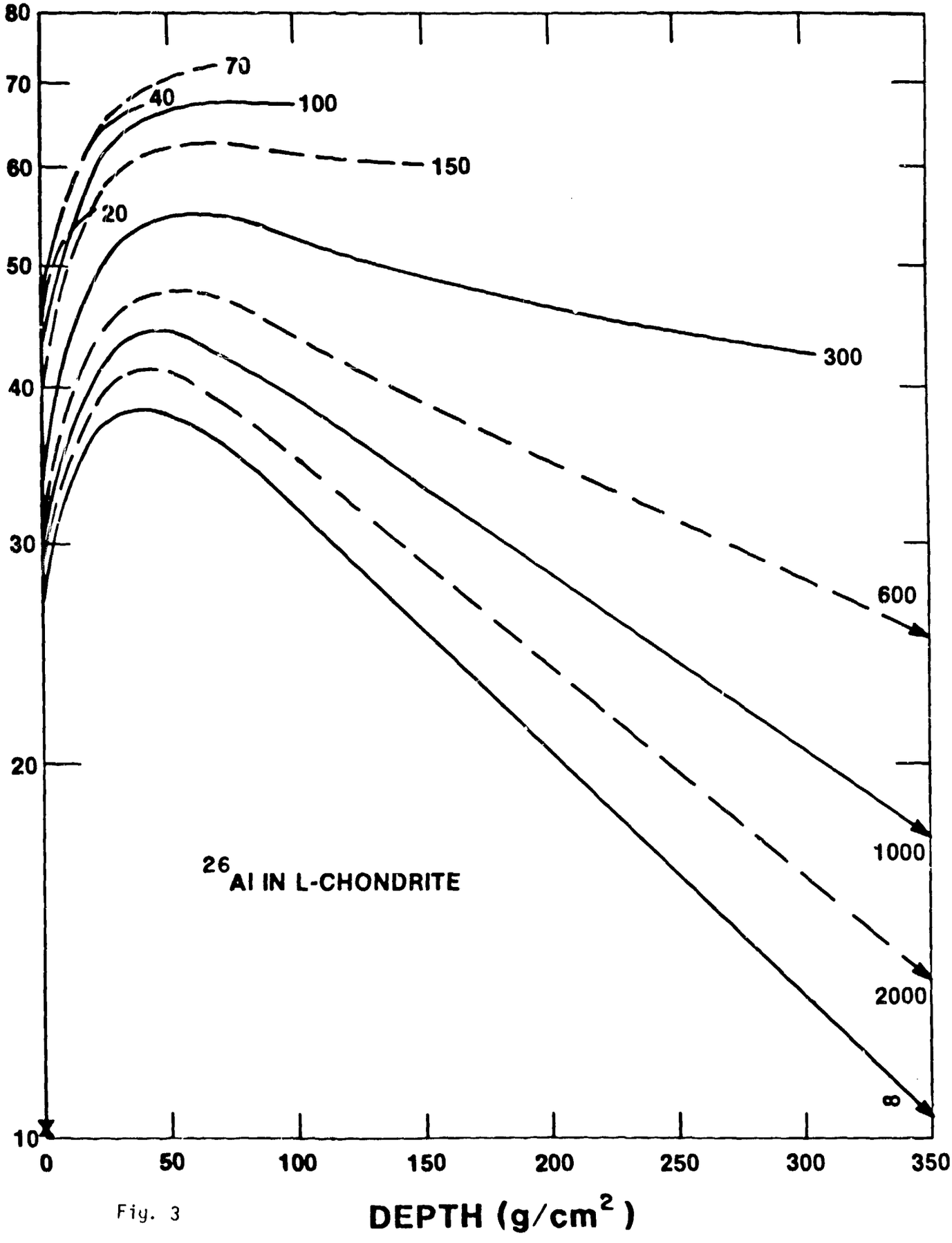
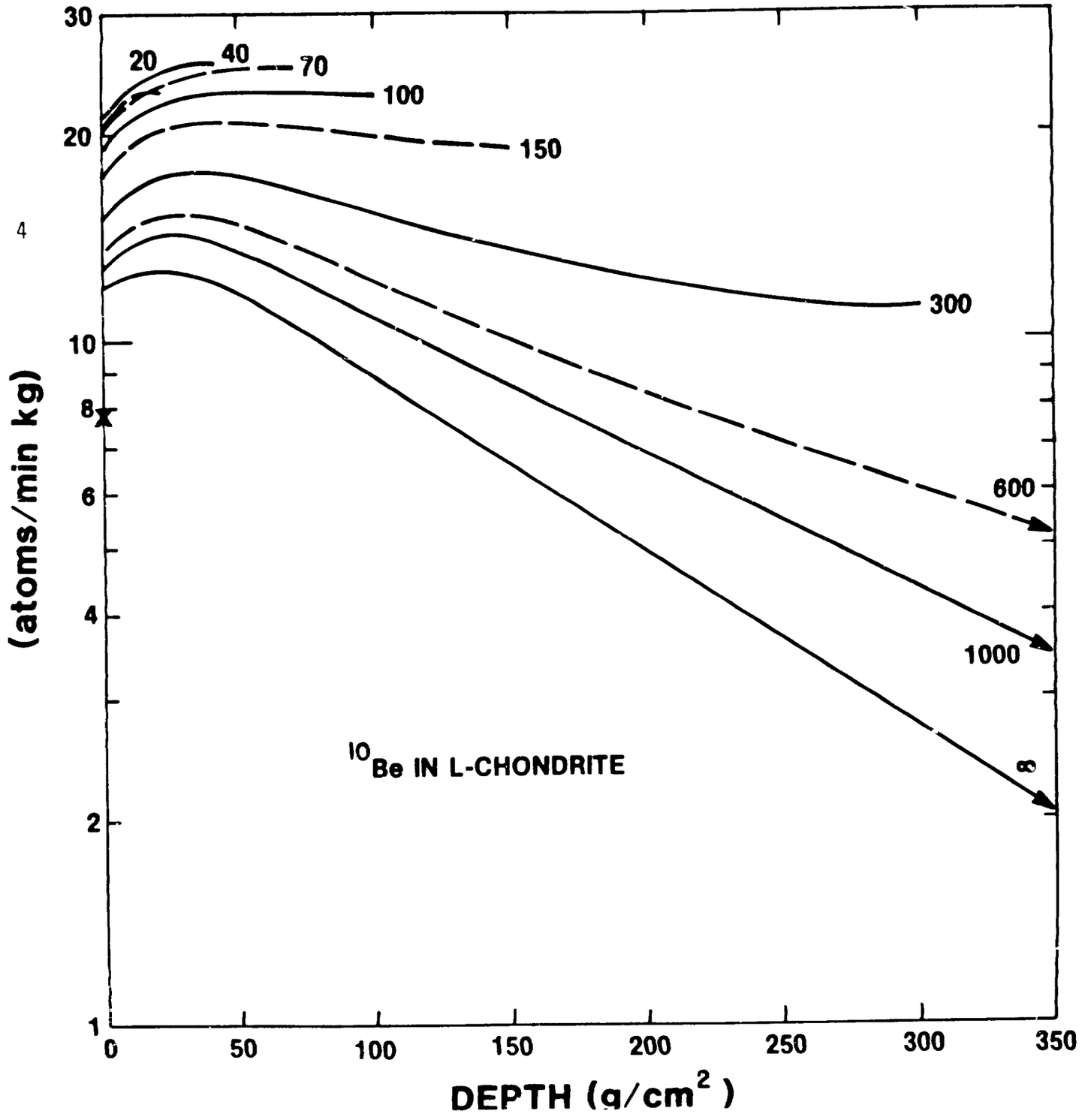

80
70
60
50
40
30
20
10
0
50
100
150
200
250
300
350
70
40
100
150
20
300
600
1000
2000
∞
^{26}Al IN L-CHONDRITE
DEPTH (g/cm^2)

Fig. 3

Fig. 4


30
20
10
8
6
4
2
1
(atoms/min kg)
0
50
100
150
200
250
300
350
DEPTH (g/cm^2)
20
40
70
100
150
300
600
1000
∞
^{10}Be IN L-CHONDRITE

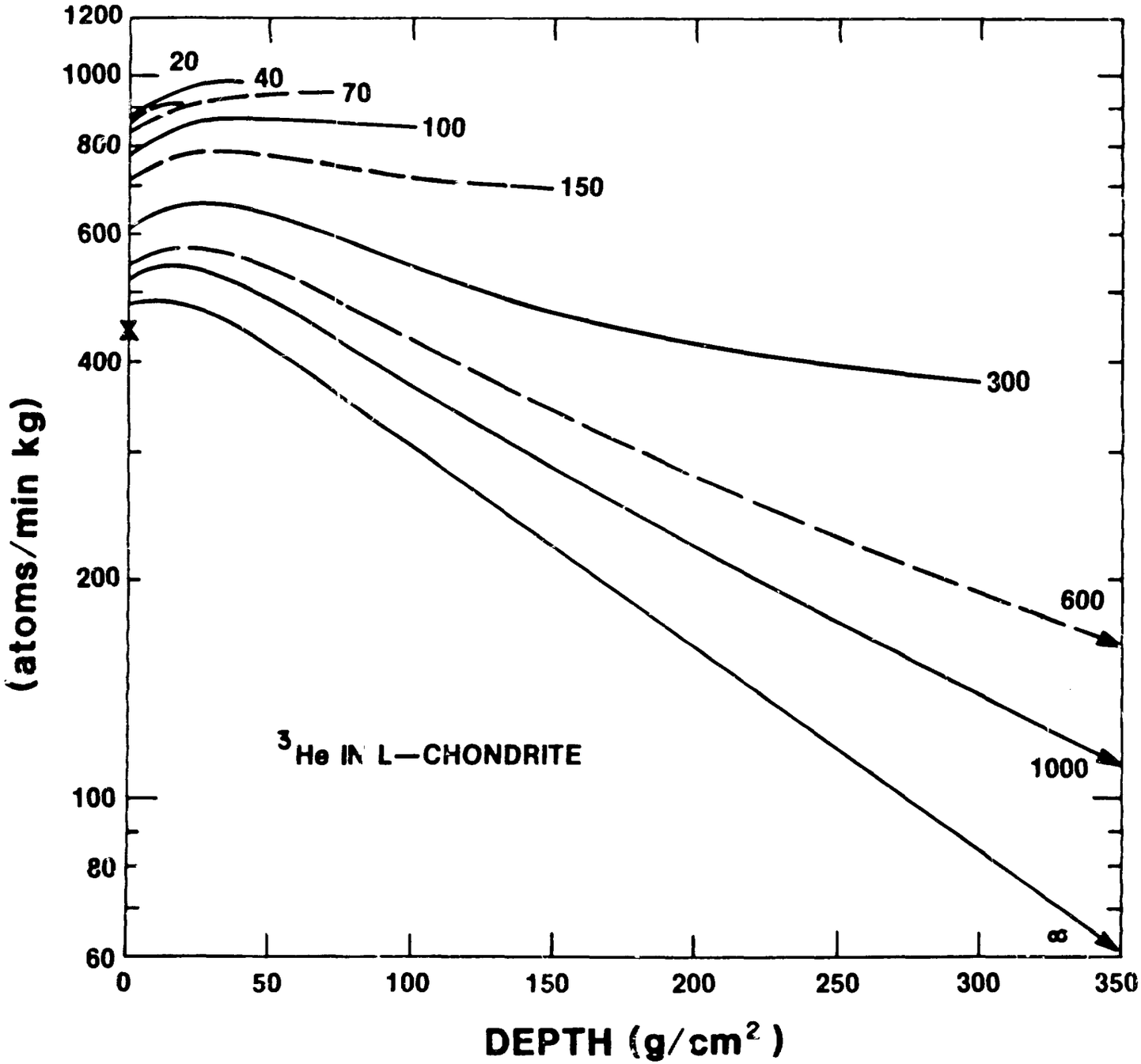

1200
1000
800
600
400
200
100
80
60
(atoms/min kg)
20
40
70
100
150
300
600
1000
∞
^{3}He IN L—CHONDRITE
0
50
100
150
200
250
300
350
DEPTH (g/cm^2)

Fig. 5

Fig. 6

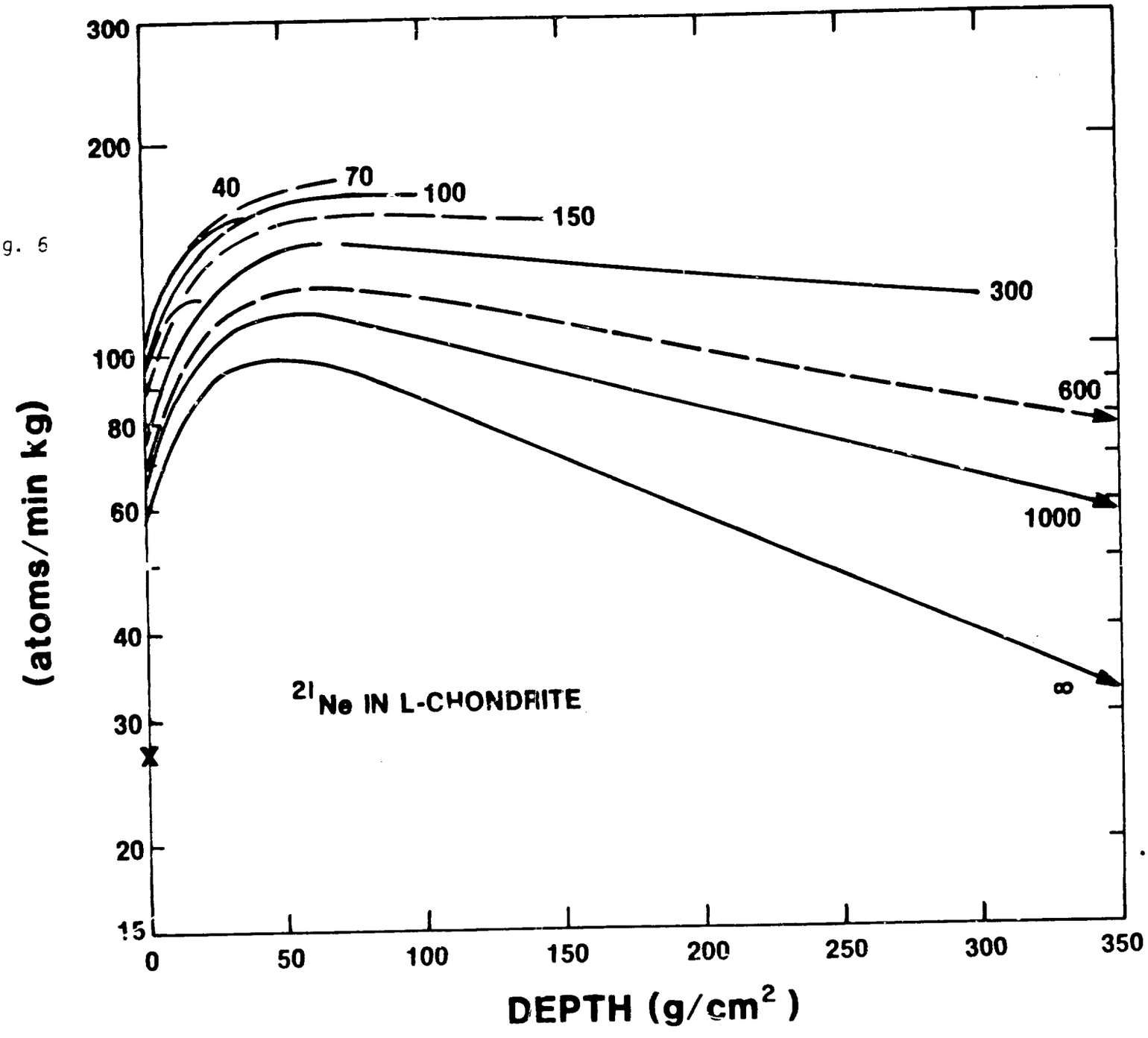
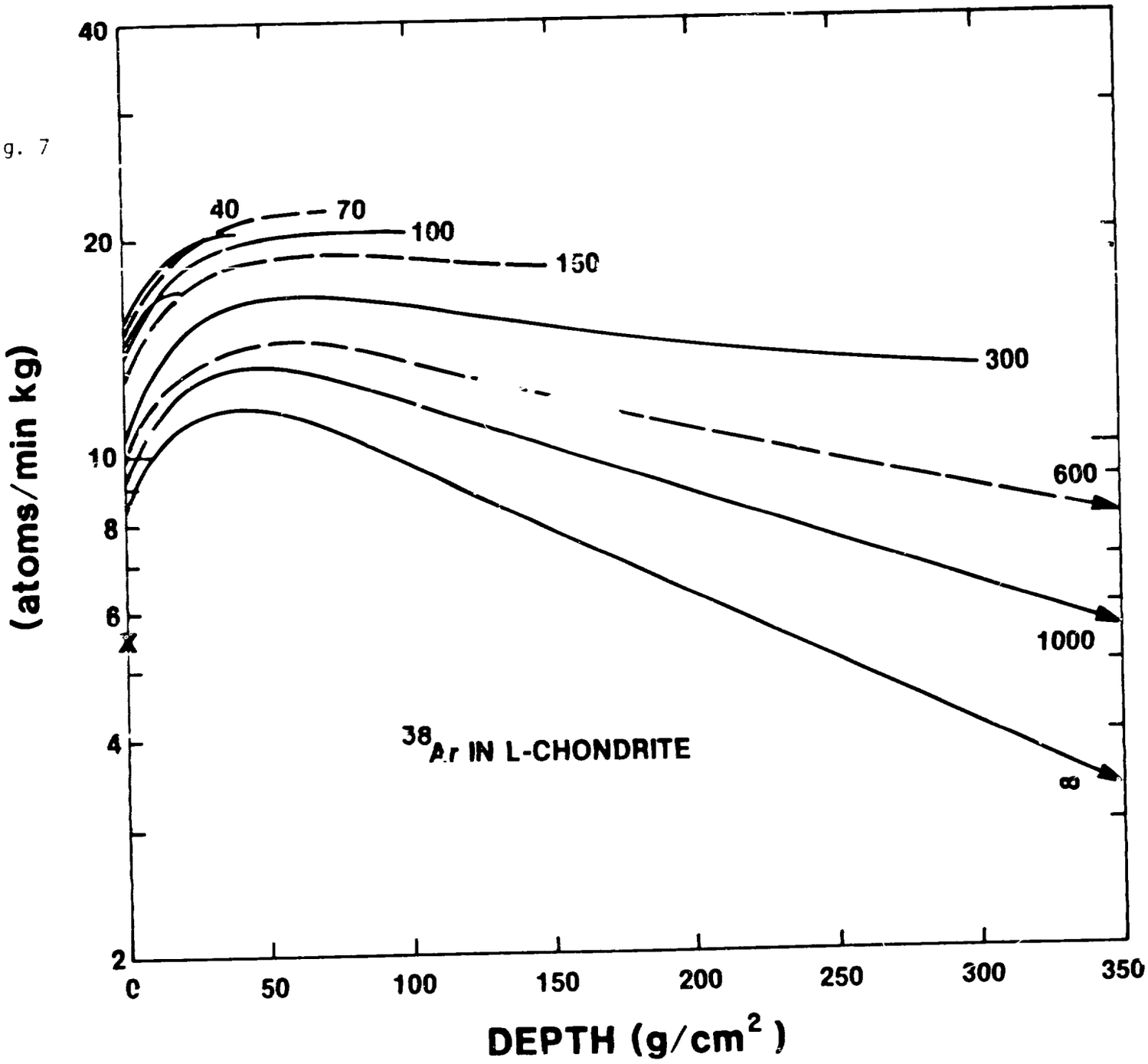

300
200
100
80
60
40
30
20
15
(atoms/min kg)
40
70
100
150
300
600
1000
∞
^{21}Ne IN L-CHONDRITE
0
50
100
150
200
250
300
350
DEPTH (g/cm^2)

Fig. 7


40
20
10
8
6
4
2
(atoms/min kg)
40
70
100
150
300
600
1000
∞
^{38}Ar IN L-CHONDRITE
0
50
100
150
200
250
300
350
DEPTH (g/cm^2)