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MEASUREMENT AND INTERPRETATION OF THE ISOTOPIC COMPOSITION OF HYDROGEN AND HELIUM COSMIC RAY NUCLEI BELOW 75 MeV/NUCLEON

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ABSTRACT

The differential energy spectra of the hydrogen and helium isotopes of the galactic cosmic radiation have been measured in 1965 and 1966 by the highly eccentric satellites OGO I and IMP III. The energy ranges were respectively 20 to 50 and 30 to 90 MeV/nucleon.

The measured ratio $\Gamma_d = H^2/He^4$ shows a very steep positive slope ($\geq E_{kin}^{+3}$) as a function of energy between 20 and 50 MeV/n. At 50 MeV/n, Γ_d is roughly 0.25. These results are in qualitative agreement with the measurements performed by the University of Chicago group on IMP III. The measured ratio $\Gamma_{He} = He^3/He^4$ is roughly 0.05 at 60 MeV/nucleon, and decreases at lower energies.

In order to understand the energy dependence of Γ_{He} and especially of Γ_d (Γ_d is not affected by the solar modulation), we investigated the creation of deuterium and He^3 through fragmentation of cosmic ray and interstellar He^4 nuclei, and proton-proton reactions (assuming no injection of these isotopes at the source).

We have used a Monte Carlo technique to propagate the cosmic ray protons and He^4 nuclei from the source to the earth. A critical survey of the available cross section data has been made. The ionization loss,

the energy dependence of the cross sections, the reaction kinematics have been taken into account. The elastic scattering, acceleration in space and solar modulation have not.

We have systematically tried to fit the data with different source spectra and propagation models. Our present results completely rule out a total energy, and favor kinetic energy source power spectrum. We discuss the bearing of different non-local propagation models (open model, closed model, injection at one time; different energy dependences of the mean "vacuum pathlength") on Γ_d and Γ_{He}.

We report measurements of the hydrogen ($\Gamma_d = d/H^1$) and helium ($\Gamma_{He} = He^3/He^4$) isotopic abundance ratios and the results of a propagation calculation studying the bearing of different source and propagation models on Γ_d and Γ_{He}.

A. Measurements of Γ_d and Γ_{He}:

The measurements of Γ_d and Γ_{He} have been performed on board highly eccentric-orbiting satellites IMP-III and OGO-I respectively, while the satellites were outside the earth's atmosphere and magnetosphere. Γ_d has been measured continuously between June 1965 and September 1966 and Γ_{He} during 1965 at solar minimum.

The detector used was a dE/dx vs. E scintillator telescope, previously described by Balasubrahmanyan et al. (1966). The energy ranges were 20 to 50 MeV/nucleon for deuterons and 30 to 90 MeV/nucleon for He^3. The data were analyzed by the mass-histogram technique. High nuclear interaction background and gain changes complicated the procedure and further analyses may slightly change the values given here.

The resulting ratios Γ_d and Γ_{He} are shown in figure 1, together with measurements by others. Our Γ_{He} values are identical to those of Hagge et al. (1966).

It is seen that our measurement of Γ_d agrees roughly with the results of Fan et al. and a very steep positive slope for Γ_d between 20 and 50 MeV/n seems established. The Γ_{He} we find also has a positive slope between 30 and 90 MeV/n but the values are significantly higher than those found by Fan et al.

B. The Propagation Calculation:

1. Objective: Our objective was to study the implication of the measured He^3/He^4 and especially d/He^4 (which is not affected by solar modulation) ratios on different source spectra and non-local propagation models.

2. Assumptions and Features of the Calculation:

a. There is almost no d or He^3 in stellar matter. We therefore assume that the observed cosmic ray deuterons and He^3 nuclei are produced exclusively by nuclear reactions between cosmic ray nuclei and interstellar matter.

b. The source spectra of protons and He^4 nuclei were assumed identical within a factor 6 of the abundance ratio. The differential spectra which we have tried were shaped as power laws with an exponent -2.5 in total energy W, rigidity R, or kinetic energy E.

c. The assumed interstellar matter composition was 90% H^1 and 10% He^4 (in numbers).

d. The energy loss through ionization of both source and secondary particles has been taken into account. The effect of the elastic scattering has been neglected.

e. A possible gradual acceleration in space has not been taken into account.

f. Nuclear Reactions (cross sections and kinematics)

Among the reactions leading to H^2, H^3 and He^3, those involving proton and He^4 as interacting particles are dominant, as shown by Biswas et al. (1967). Note that H^3 decays into He^3 with a 12-year period; production of H^3 and He^3 will therefore be treated together. Therefore we have to consider:

(1) the fragmentation of cosmic ray He^4 nuclei on interstellar protons (or He^4 nuclei),

(2) the fragmentation of interstellar He^4 nuclei by cosmic ray protons, and

(3) the interaction between cosmic ray protons and interstellar protons.

This involves the study of proton-He^4 and proton-proton interactions. We have made a critical survey of the available data on the cross-sections and kinematics of these reactions. Some corrections and renormalizations have been applied to the existing data. There is no space here for this study, which will be published elsewhere. The resulting cross-section picture is summarized in figure 2.

The destruction of the created deuterons and He^3 nuclei by a second nuclear interaction has not been considered in the present stage of the calculation.

g. Solar Modulation: The solar modulation has not been included in the calculation. Note that, since d and He^4 nuclei have the same charge-to-mass ratio, the ratio of their abundances will not be affected by solar modulation. The He^3/He^4 ratio can be only decreased by solar modulation.

h. Path-length: Let us first define the notion of "vacuum path-length" introduced by Cowsik et al. (1967). We will call "vacuum path-length" the distance which a particle would have gone through between the source and the solar system (including scattering), if no matter had been present to eventually remove the particle from the cosmic radiation through braking or nuclear interaction. The choice of a vacuum path-length distribution defines a propagation model.

Clearly, the "actual path-length distribution" i.e. the distribution of the path-lengths passed through by the particles which do actually reach the solar system, will be different from the vacuum path-length distribution; it will be systematically shifted towards shorter path-lengths, for the longer the vacuum path-length, the higher the probability of a particle being removed by braking or nuclear interaction. This distortion of the vacuum path-length distribution will be highly charge and energy dependent at lower energies.

We have essentially considered 3 types of models:

(1) Steady state closed models:

In these models there exists some localization of the source and the vacuum trajectories of the particles have not been completely randomized by scattering. Then the particle that reaches the solar system has kept some memory of the position of the source, and an "average source distance" can meaningfully be defined, as seen from the earth. One further condition to be realized for this model to work is a negligible leakage* from the system between the source and the earth.

If these conditions are realized, a diffusion picture arises and the vacuum path length distribution will be something like a broad Gaussian. The kind of model has been worked out by Balasubrahmanyan Boldt, and Palmeira (1965) in the case of a point source, using the equations of the Brownian motion. They find a Gaussian-like distribution with a standard deviation equal to $\sqrt{\frac{2}{5}} = 0.63$ times the peak value.

(2) Steady state open models:

In these models, either there exists no localization of the source (earth seen in a quasi-infinite homogenous source medium, as for example supernovae scattered all over the galaxy), or there exists a localization but either the leakage is dominant between the source and the solar system, or the vacuum trajectories of the particles have been completely randomized by the scattering. Anyway, the particle

* A particle is considered "leaking" when it gets into a zone from which it has a negligible probability to reach the earth at any time (for example outside the galaxy). In a steady state picture with continuous production of cosmic rays the introduction of such a sink is necessary. Let us note that the introduction of the braking of particles provides a supplementary sink which, no doubt, will be dominant at low energies; but to assume that ionization braking is the only sink would lead at relativistic energies to huge path-lengths, proportional to the energy. This is in direct contradiction with the mean path-lengths observed.

that reaches the solar system has no memory of any source position, and no "average source distance" can meaningfully be defined, as seen from the earth.

Then, the leakage from the system will be the dominant factor shaping the distribution of the vacuum path-lengths. Many models can be imagined assuming different physical conditions for the leakage from the galaxy. One possible simple assumption is that the probability of leakage is equal on any path length element ΔS (physically, the particle often reaches the border of the system, but has a low probability of escape at each time); this model leads to an exponential distribution of the vacuum path-length. Such a model has been proposed by Cowsik et al. (1967).

(3) "Cosmic Ray Big Bang" Model:

If the cosmic ray flux observed today is the result of one ancient event at some time t_1 ago, and the escape is negligible, then the particles will have gone through vacuum path-lengths

$$S_V \propto \int_0^{t_1} v(t)\, dt.$$

This kind of model has been described by Durgaprasad (1967) and is suggested from recent data by Webber (1967) with $S_V = 3$ g/cm^2 for relativistic particles.

Whichever of the steady state models is considered another parameter remains to be fixed: the energy dependence of the mean value

$\bar{S}_V$ of the vacuum path-length distribution, whichever shape it has. About its energy dependence, we know almost nothing. Any model would assume precise physical conditions for scattering and leakage. It is plausible that the mean vacuum path-length is a decreasing function of the rigidity, since low rigidity particles are more easily trapped. We have made our calculations with two extreme models:

(a) A very sharp rigidity R dependence of $\bar{S}_V$

$$\bar{S}_V \quad \alpha \quad \frac{1}{R}$$

as in Cowsik et al. (1967); and

(b) $\bar{S}_V$ independent of the rigidity.

i. The method used for the calculation was a Monte Carlo technique.

3. Results:

a. Remarks:

Typically 30% of the deuterons observed below 200 MeV/n are due to the interaction of cosmic ray protons with interstellar He^4 and H'. Most of those above 80 MeV/nuc are due to the reaction: $p + p \rightarrow \pi^+ + d$. The break up of interstellar He^4 nuclei by cosmic ray protons is unimportant for the formation of He^3.

On the other hand, it must be kept in mind that low energy secondaries observed at the earth have generally been created at medium energies and slowed down later on.

b. Source Spectra:

We have limited our study to spectra with a unique power law with an exponent -2.5 in total energy W, rigidity R and kinetic energy E, over the whole energy range.

For any propagation model, the steeper the negative slope of the source spectrum, the steeper the positive slope of Γ_d at low energy. Indeed, low energy source particles, having a small range, have a low probability of interaction. Therefore, the addition of a large number of low energy primaries will scarcely affect the number of secondaries and strongly decrease the ratio of secondaries to primaries.

The criterium of fitting the very steep experimental slope of Γ_d between 20 and 50 MeV/nuc. allows a rejection of a total energy source spectrum (exponent -2.5), which, for all the propagation models considered, gives for Γ_d a spectrum roughly flat down to a few MeV. An extremely steep source spectrum, at least as steep as a power law in kinetic energy seems favored. This applies for low energies, typically up to a few hundred MeV.

Therefore, all the further studies have been made with a source power law in kinetic energy. In figure 1, we have plotted the calculated spectra for one typical propagation model.

c. Propagation models:

In figure 3, we have plotted for different propagation models the calculated spectra of Γ_d and Γ_{He} for a kinetic energy source power spectrum. The mean value of the different path-length distributions have been chosen in order to get for Γ_d the measured order of magnitude at 50 MeV/nuc.

Models with the strong rigidity dependence of the average vacuum path-length $\overline{S}_V \propto \frac{1}{R}$ lead to less steep slopes of Γ_d at low energies. Indeed, these models allow fewer primaries with medium energy at the source to reach the earth as low energy primaries. For the present stage, we cannot draw any conclusion concerning an open or closed model. High energy data are badly needed.

The model with a unique injection at once (3 g/cm^2 for relativistic particles) does not seem appropriate.

4. Conclusions:

To be stressed is the need of an extremely steep source spectrum at lower energies, probably steeper than a kinetic energy power law with an exponent -2.5, in order to fit the modulation independent deuteron data. A unique shape of the energy spectrum over the whole energy range may well be an over-simplification.

High energy data are badly needed for more precise study of the propagation models.

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Figure Captions

Figure 1: Measured and calculated Γ_d and Γ_{He} with a typical propagation model for a total energy W, a rigidity R, and a kinetic energy E source power spectrum (exponent -2.5).

Figure 2: Cross sections for H^2, H^3 and He^3 producing reactions involving p and He^4 as interacting particles.

Figure 3: Measured and calculated Γ_d and Γ_{He} with a kinetic energy source power spectrum (exponent -2.5) for different propagation models.

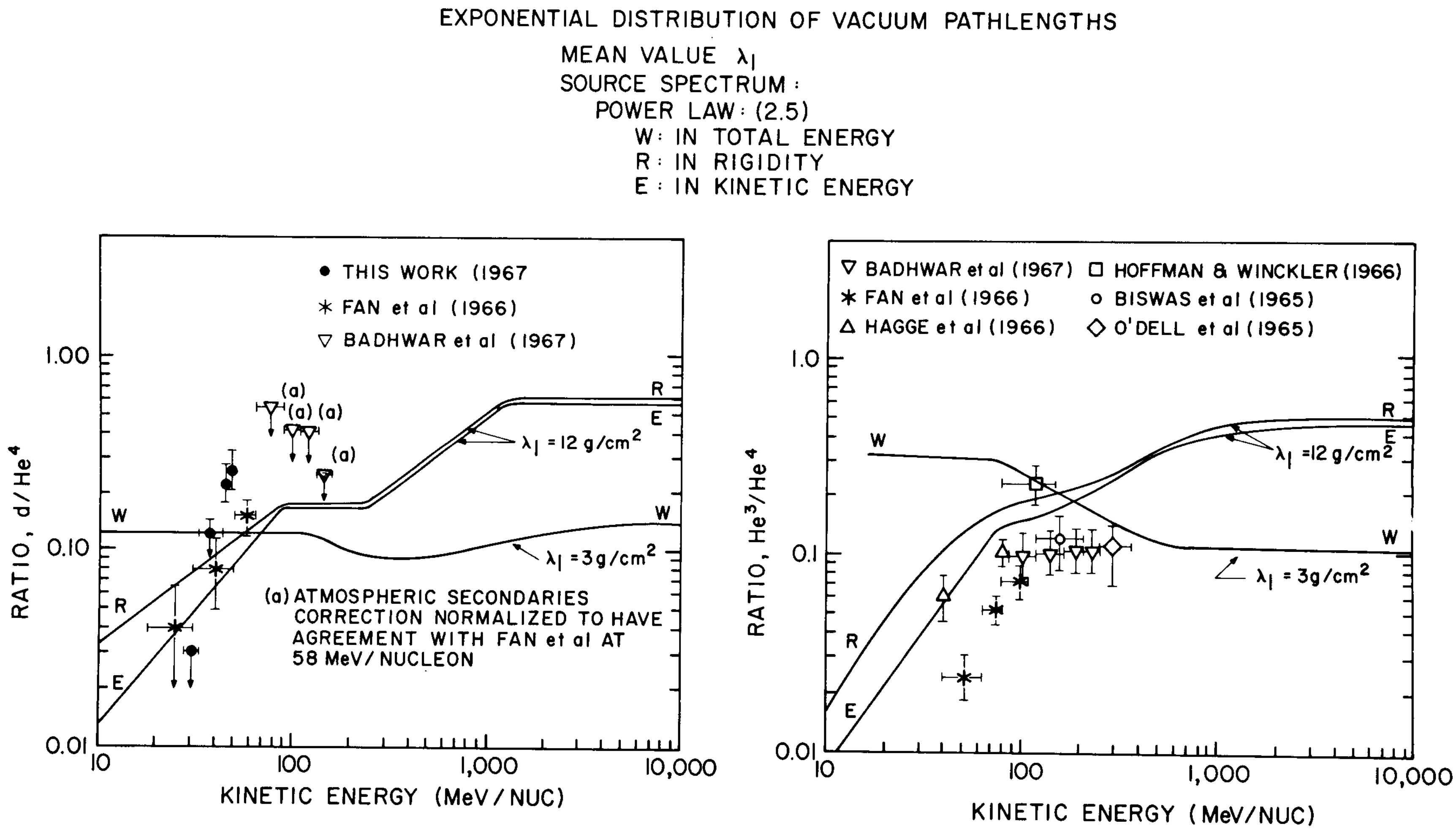
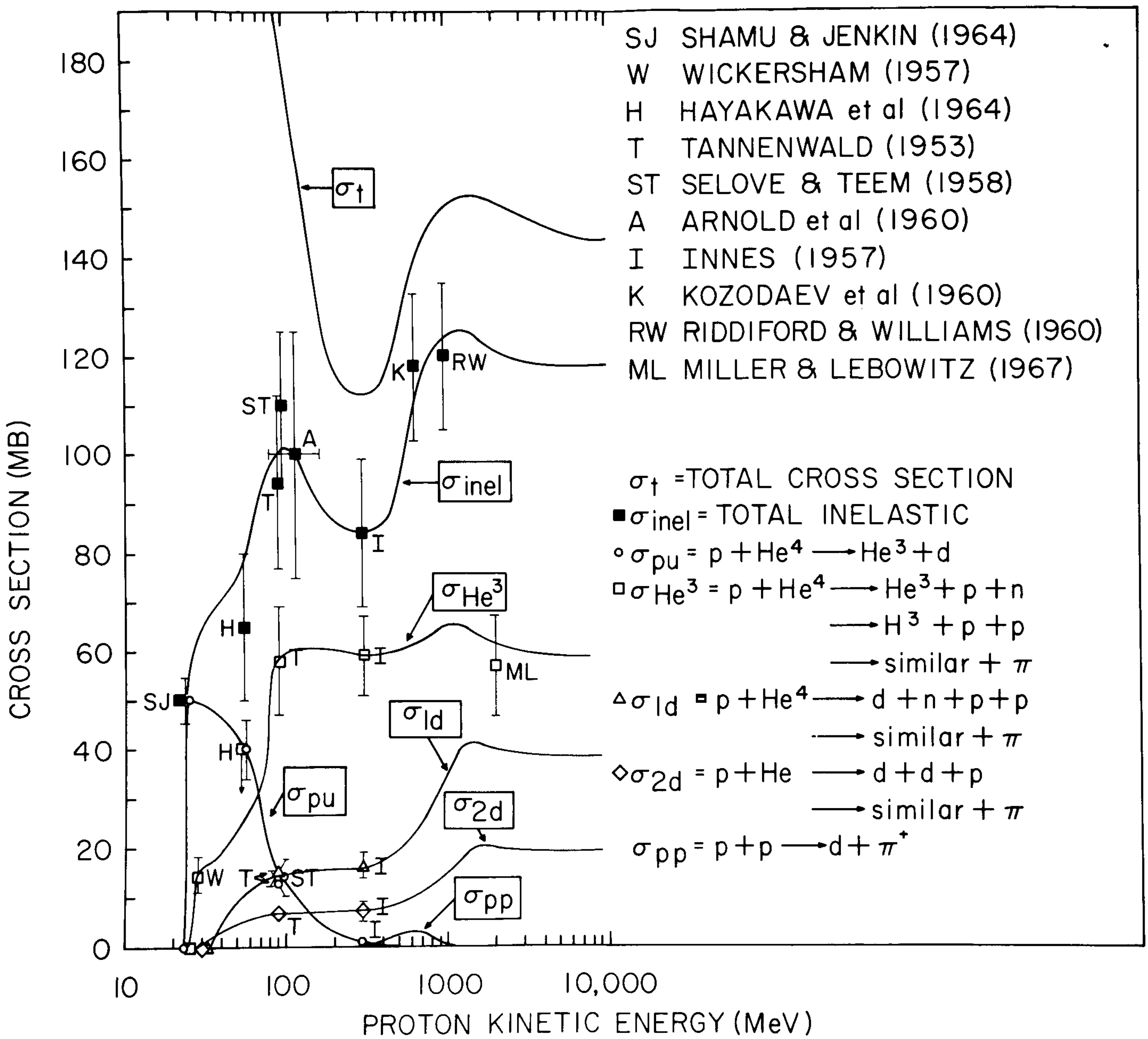

EXPONENTIAL DISTRIBUTION OF VACUUM PATHLENGTHS
MEAN VALUE λ_I
SOURCE SPECTRUM:
POWER LAW: (2.5)
W: IN TOTAL ENERGY
R: IN RIGIDITY
E: IN KINETIC ENERGY
● THIS WORK (1967
* FAN et al (1966)
▽ BADHWAR et al (1967)
(a)
(a) ATMOSPHERIC SECONDARIES CORRECTION NORMALIZED TO HAVE AGREEMENT WITH FAN et al AT 58 MeV/NUCLEON
λ_I = 12 g/cm^2
λ_I = 3g/cm^2
W
R
E
RATIO, d/He^4
1.00
0.10
0.01
10
100
1,000
10,000
KINETIC ENERGY (MeV/NUC)
▽ BADHWAR et al (1967)
□ HOFFMAN & WINCKLER (1966)
* FAN et al (1966)
o BISWAS et al (1965)
△ HAGGE et al (1966)
◇ O'DELL et al (1965)
RATIO, He^3/He^4
1.0
0.1
0.01

Figure 1



CROSS SECTION FOR REACTIONS BETWEEN p AND He^4
LEADING TO d, H^3, OR He^3

Figure 2

SOURCE SPECTRUM : KINETIC ENERGY POWER LAW ($E^{-2.5}$)

DISTRIBUTION OF VACUUM PATHLENGTHS –

$E_{R^{-1}6}$: EXPONENTIAL, MEAN VALUE $\lambda_1 \propto 1/R$ (NORMALIZED: 6 GM/CM^2 AT 3 GeV)

E_{12} : EXPONENTIAL, MEAN VALUE $\lambda_1 \equiv 12$ GM/CM^2

$G_{R^{-1}1}$: GAUSSIAN, (BALASUBRAHMANYAN et al, 1966), PEAK VALUE $\propto 1/R$ (NORMALIZED: 1 GM/CM^2 AT 3 GeV)

G_8 : GAUSSIAN, (BALASUBRAHMANYAN et al, 1966), PEAK VALUE $\equiv 8$ GM/CM^2

I : INJECTION AT ONCE (3 GM/CM^2 FOR RELATIVISTIC PARTICLES)

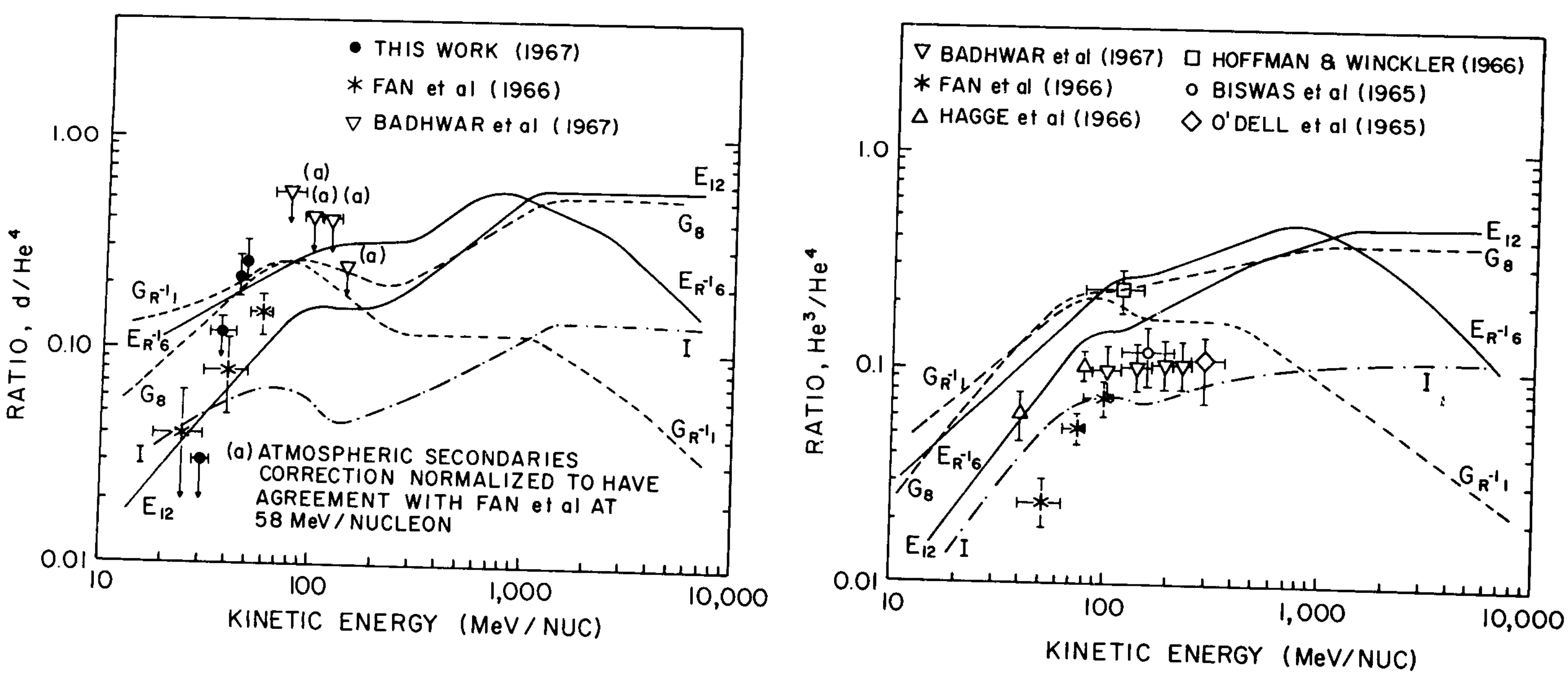


Figure 3