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MEASUREMENT OF THE FLUXES OF GALACTIC COSMIC RAY ^{2}H and ^{3}He in 1972-3

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I. INTRODUCTION

It has long been expected that a close generic relation would exist between ^{1}H, ^{2}H, ^{3}He and ^{4}He, the four stable isotopes of hydrogen and helium. ^{2}H and ^{3}He should be essentially absent in the source region as a result of their rapid consumption in nuclear burning processes. The relatively large abundances of these isotopes observed in cosmic rays can then only be explained in terms of spallation processes occurring either in the source, or during subsequent travel through the interstellar medium. These isotopes are offspring of the same parents, i.e. either ambient-interstellar or cosmic-ray hydrogen and helium. In addition, the reaction cross-sections and kinematics of their production are somewhat similar. Using the measured spectra of the four isotopes and assuming that ^{1}H and ^{4}He have similar source spectra, self-consistent models of interstellar propagation and solar modulation were developed for low energy (i.e. ~20-100 MeV/nuc) H and He (Ramaty and Lingenfelter, 1969; Meyer 1974; Biswas and Ramadurai, 1973). In this paper we present improved measurements of the stable isotopes of H and He during a period of low solar modulation. These measurements are in significant disagreement with earlier results and indicate that low-energy ^{1}H and ^{4}He must have very different source spectra with ^{4}He being dominated by a strong "local" source.

The new results in this paper are from experiments on both the IMP VII and Pioneer 10 spacecraft which are vastly improved over the experiments used for the earlier Goddard-University of New Hampshire results (Baity et al. 1971). Two effects have combined to improve the quality of the ^{2}H measurements. First, the detector background has been reduced due to an extended anti-coincidence shield and a reduction of the amount of matter surrounding the telescope. Second, the measurements were taken during 1972, a period where the low-energy intensity had returned to the same value as the last solar minimum (1965). Intensities were therefore large and the effective signal-to-noise ratio was maximized. In the case of ^{3}He, three-parameter analysis on Pioneer 10 has allowed us to achieve lower background levels than in earlier measurements.

Earlier ^{2}H measurements (Meyer et al. 1968; Fan et al. 1966; Hsieh and Simpson 1969; Baity et al. 1971; Hsieh et al. 1971) taken as a whole have presented a somewhat confusing picture. The earliest measurements were complicated by the necessity of large background subtractions. Later measurements (during 1967-69) of the Chicago group in some instances showed relatively low background levels. Measurements in 1967-69 on separate satellites by the Goddard and University of New Hampshire groups were, however, in disagreement with the Chicago results. Intercomparison of data is further complicated by the time variations introduced by solar modulation. The earliest treatments assumed that by taking abundance ratios of species with the same charge-to-mass ratio, the effects of solar modulation would cancel. It has since been realized that such a simple picture is not, in fact, correct. Energy-loss effects could produce variations in the abundance ratios over the solar cycle.

Theoretical calculations of the production of ^{3}H and ^{3}He in interstellar space have been carried out by several authors (Ramaty and Lingenfelter 1969; Meyer 1971, 1974; Biswas and Ramadurai 1973; Comstock et al. 1972), with the most comprehensive being that of Meyer (1971, 1974). These calculations have all assumed that the spectra of protons and helium are identical at the sources. They have also made standard assumptions about the distributions of path-lengths traversed by cosmic rays in our galaxy (i.e. either slab or exponential). Recent measurements, however, cast considerable doubt on these assumptions. Such observations include the existence of a flat helium spectrum in the 10-60 MeV/nucleon interval and the presence of an unusual enhancement of the abundance of oxygen and nitrogen at low energies (Garcia-Munoz et al. 1973; Van Hollebeke et al. 1973; McDonald et al. 1974). This evidence points to the existence of a nearby source whose composition is different from the bulk of the cosmic radiation at higher energies. Previously, ratios of $^{3}H/^{4}He$ and $^{3}He/^{4}He$ have been studied in the context of the theoretical treatments mentioned above. Clearly, if a nearby source of low-energy helium is present, which has traversed a relatively small amount of matter and thus has not caused the production of a significant amount of ^2H or ^3He, then these abundance ratios will be suppressed, particularly at low energies. This seems to be the most likely explanation for the low ratios which we report here.

II. EXPERIMENTAL RESULTS

The deuterium results are derived from the Goddard experiment on IMP 7 which is in earth orbit (apogee ~ 40 earth radii). Data was accumulated during the period September - December, 1972. ^3He data comes from the Goddard-University of New Hampshire experiment on the Pioneer 10 Jupiter mission and was accumulated between March 1972 and March 1973, a period when Pioneer 10 traveled between 1 and 4 AU. In all cases where ratios are given, both species are measured on the same spacecraft. Gradient effects are expected to have a negligible influence on the results presented here. The helium gradient between 1.0 and 2.75 AU is < 20%/AU (Teegarden <u>et al</u>. 1973; McKibben <u>et al</u>. 1973). Finally, we have determined the $^3He/^4He$ ratio during an early period when Pioneer 10 was between 1.0 and 1.5 AU and find no change in the ratio.

Stringent time selection criteria were used for both the IMP and Pioneer data to insure that solar particle contamination did not enter. In both cases it was required that the proton intensity at ~ 10 MeV be at background level.

The resolutions of the IMP 7 and Pioneer 10 instruments are shown respectively in Figs. 1a and 1b. The detectors are of the dE/dx vs. E type, and the plots shown are distributions of events as a function of distance from the centroid of the characteristic particle track.

In Figure 1a, the distribution in each plot has been transformed back into energy-loss space so that the horizontal scale is roughly proportional to the energy loss in the dE/dx detector. This is done since detector background tends to follow a power law in energy-loss space as can be seen in the plots. The background subtraction in the lowest energy interval (20-30 MeV per nucleon) introduces a rather large uncertainty. The error bars in the following reflect both statistical errors and estimated uncertainty in the background subtractions.

The ^{3}He distributions in Fig. 1b are constructed in essentially the same fashion as the ^{2}H distributions in Figure 1a. However, since the background levels in Figure 1b are much lower, there was no need for a transformation back into dE/dx space. It is clear that in the two lowest energy intervals there is no positive evidence for a finite flux of ^{3}He. We therefore quote only upper limits at these energies. It is also clear that in the two highest energy bins ^{3}He is quite well resolved from ^{4}He with little or no background subtraction necessary. These data illustrate the power of the three-parameter (double dE/dx vs. E) analysis technique employed in our Pioneer 10 telescopes and show that such a detector without an anti-coincidence is capable of performing extremely high-quality low-background measurements.

The ^{2}H spectrum derived from Figure 1a is shown in Figure 2a along with other measurements during the 1965-1973 period. During the period of our measurements the proton and ^{4}He intensities at $\sim$ 50 MeV/nucleon had returned to essentially the same values as at the last solar minimum.

The 1965 data points are, however, roughly a factor of four higher than our 1972 points. Furthermore, the Chicago 1967 data is also higher than our 1972 spectrum. During 1967 both the proton and helium intensities were reduced by roughly a factor of two from their solar minimum values. It therefore appears impossible to reconcile either the 1965 or the Chicago 1967 results with the 1972 measurements. We note, however, that the 1967-68 upper limit of Baity et al. 1971 is substantially lower than the Chicago 1967 spectrum and is quite consistent with the 1972 results.

The ^{3}He spectra at various times during the last solar cycle are shown in Figure 2b. Note that our 1972-73 points are at the same level as the University of Chicago data from the last solar minimum (1965). This is consistent with the behavior of ^{4}He which, in 1972, had returned to nearly the level of the last solar minimum. Comparison of our 1972-73 data and the University of Chicago 1967 data would imply a rather strange behavior for the ^{3}He modulation. The modulation, in fact, is apparently smallest (i.e. close to zero) at ~ 10 MeV per nucleon and increases to more than a factor of two at 100 MeV per nucleon. We regard this with some suspicion, particularly in the context of the earlier problems with the ^{2}H measurements, but feel that modulation cannot be ruled out as the explanation for this behavior.

Rygg and Earl (1971) presented data that is consistent with a proton energy spectrum of the form $J \cong AT$ (where A is a constant and T is the kinetic energy) over a kinetic energy interval from 30 to 200 MeV.

Their measurements have also indicated that this behavior persists over at least a major fraction of the solar cycle. Van Hollebeke et al. 1973 have shown that some departure from this behavior exists at low energies (20-80 MeV) where the spectral index was observed to vary between 0.7 and 1.4 over the last solar cycle. This behavior is a consequence of the presence of a significant amount of energy loss in the interplanetary medium. If the majority of particles seen at 1 AU have been cooled down from higher energies (which generally will be true if the interstellar spectrum is not over-abundant in low energy particles), and if the gradients are small, a spectrum proportional to energy follows. The Pioneer 10 measurements have conclusively shown that small gradients exist (Teegarden et al. 1973; McKibben et al. 1973; Van Allen 1972). Because ^2H and ^3He are secondary products of interactions of higher energy primaries, it is extremely unlikely that their interstellar spectra are very steeply rising at low energies (see, for example Meyer 1971). One would therefore quite reasonably expect these isotopes to follow the approximate $J = AT$ behavior.

Referring again to Figure 2, we see that the Chicago 1969 and Goddard-University of New Hampshire 1972 ^2H spectra are consistent with $J \cong AT$, whereas the Chicago 1967 spectrum is somewhat flatter. The data in 1965 are inadequate to define a spectral slope. For ^3He the data are all consistent with a slope of unity with the exception of the two lowest energy points of the Chicago 1967 spectrum. The background subtraction, however, for these two points was quite large (Hsieh and Simpson 1970) so that their reliability must be considered not as great as the rest of the data.

Based upon the above considerations we propose the following as a self-consistent data set: (1) for ^2H; Goddard-University of New Hampshire 1967-68, Chicago 1969, Goddard 1972, Caltech 1972, (2) for ^3He; all the data in Figure 2b with the exception of the two lowest energy points of the Chicago 1967 spectrum. The Goddard 1965 and Chicago 1965 data have been eliminated since they disagree with the 1972 results. The Chicago 1967 data has been eliminated since it is also higher than the 1972-73 data and is inconsistent with $J \cong AT$ as well. We note that this data set is different from either of the self consistent sets proposed by Meyer (1974). Meyer used the $^2H/^4He$ and $^3He/^4He$ ratios as his principal criteria. Due to the probable presence of a nearby source of low-energy helium,we believe that these ratios are of limited usefulness and have instead used as our criteria the relative modulation and the spectral shape of the various measurements.

III. DISCUSSION

Our measured 1972 ^2H and ^3He spectra are compared with calculated interstellar spectra (Meyer 1971) in Figure 3. Two extreme assumptions for the source spectral shape (kinetic-energy and total-energy power laws) are shown. We note, first, that the two calculated spectra differ typically by two orders of magnitude at energies below 100 MeV/nucleon. Thus one can place only very broad limits on the magnitude of the modulation from these data. For ^2H the modulation could be anywhere between a factor of 10 and 1000, and for ^3He 5 and 1000. Second, it is apparent that the measured ^2H and ^3He spectra in 1972 are the same within errors. At the same energy/nucleon the rigidity of ^2H is 33% larger than that of ^3He so that the modulation of ^2H would be expected to be less than or equal to that of ^3He (assuming that the interstellar spectral shapes are not too different). Figure 3 shows that if the source spectrum is a total-energy power law, the modulation of ^2H is roughly twice as large as that of ^3He, which conflicts with the previous statement. This suggests that the source spectrum is significantly steeper than a total energy power law. The reader should be cautioned, however, that cross-sections for the production of ^2H and ^3He are in some cases as much as 50% uncertain (Meyer 1974). Therefore the possibility that the apparent difference in ^2H and ^3He modulation is due to errors in the calculated spectra cannot be ruled out.

We have discussed earlier the difficulties associated with using the $^2H/^4He$ and $^3He/^4He$ ratios as indicators of the interstellar source spectra. We shall, however, in the following, compare 1972 $^2H/^4He$ and $^3He/^4He$ ratios with calculated values in an attempt to further delineate these difficulties and to also demonstrate the need for the introduction of a nearby source for low energy helium nuclei.

The calculated $^2H/^4He$ and $^3He/^4He$ ratios of Meyer (1971) are shown in Figure 4. Hydrogen and helium spectra were assumed to have the same spectral shape, $J(T) = k\ (T+T_o)^{-2.5}$ at the source, and interstellar spectra were calculated assuming an exponential pathlength distribution with a mean of 7.0 g/cm^2. The source spectra were allowed to vary over a wide range, from a power law in total energy (T_o = 938 MeV per nucleon) to a power law in kinetic energy ($T_0 = 0$). Figure 4 illustrates that over this entire range at energies >100 MeV per nucleon the calculated interstellar $^2H/^4He$ ratio was always >0.09 and the interstellar $^3He/^4He$ ratio was always >0.07. Below 100 MeV per nucleon steep source spectra (kinetic energy power laws) produced $^2H/^4He$ and $^3He/^4He$ ratios which fell off towards lower energies, while flatter source spectra produced ratios that were either flat or increasing toward lower energies.

To proceed further we must consider how solar modulation transforms the interstellar ratio into the interplanetary ratio seen at the earth. Let us describe the modulation as follows:

$$J_e(T) = \int_E^\infty J_i\,(T')\;G\,(T,\,T')\;dT' \tag{1}$$

where $J_e\,(T)$ = cosmic ray spectrum at earth

$J_i(T')$ = cosmic ray spectrum in nearby interstellar space

$G(T,T')$ = Green's function describing the modulation.

Implicit in equation (1) is the idea that particles seen at the earth at energy T may have suffered energy losses ($= T' - T$) in penetrating the solar wind to the earth. For electromagnetic interactions (e.g. solar modulation) particles having the same mass-to-charge ratio A/Z will have the same Green's function. Let us assume that the ratio of two species having the same A/Z is measured at the earth at some energy T and has a value Γ_e. It is easy to show using equation (1) that this same ratio in interstellar space must be equal to Γ_e at some energy $T' \gtrsim T$.

With the above considerations in mind, we now return to our measured $^2H/^4He$ and $^3He/^4He$ ratios. These are compared against Meyer's calculated curves in Figure 4 (Meyer, 1971). It must be kept in mind, however, that Meyer's curves represent the <u>interstellar</u> values for the $^2H/^4He$ and $^3He/^4He$ ratios. Our data points, on the other hand, are <u>interplanetary</u> and the possible effects of solar modulation must be examined. The only way in which our data points can be considered to be in agreement with Meyer's calculations is if the adiabatic energy loss is negligible (i.e. $\lesssim$ 40 MeV per nucleon). In this case a very steep (for example, kinetic-energy power law) source spectrum is required. If energy loss is introduced it is extremely difficult to reconcile calculation and measurement since the $^2H/^4He$ and $^3He/^4He$ calculated values at higher energies are everywhere greater than our measured values.

In principle the interplanetary energy loss could be very small since in 1972 we are near solar minimum conditions,which could yield relatively unmodulated spectra. In this case, we might be able to see the strong variation with energy predicted for the interstellar ratios. Biswas and Ramadurai (1973) have shown that for models similar to Meyer's such strong variation should be absent if much energy loss is occurring. The anomalous low-energy oxygen spectrum could possibly be understood also in terms of very little interplanetary energy loss, a point to which we shall return later. Very small interplanetary modulation and energy loss would also be consistent with the interplanetary radial gradients which are observed to be very small at low energies in 1972 (Van Allen 1972, Teegarden <u>et al</u>. 1973, McKibben <u>et al</u>. 1973). However, comparison of the interstellar electron spectrum inferred from radio background measurements with that observed at the earth in 1972 (Fulks <u>et al</u>. 1973) implies there was considerable residual modulation. Using parameter values for 1972 from Fulks et al. (1973) we have estimated the energy loss using the following equation (see e.g. Gleeson and Urch 1971):

$$\Phi = \frac{\alpha T}{3} \int_r^\infty \frac{V\,dr}{K} \tag{2}$$

Here $\alpha = (T + 2m_oc^2)/(T + m_oc^2)$, m_oc^2 is the particle rest energy, V is the solar wind speed and K is the diffusion coefficient. We obtain $\Phi \sim 540$ MeV/charge which, for ^{2}H and ^{4}He, becomes ~ 270 MeV per nucleon, not a small amount at all. Hence small gradients are not generally interpreted in current modulation theory as resulting from little or no net modulation. Rather they are regarded as resulting from the earth being many scattering mean free paths inside the solar modulating region (e.g. Garrard et al. 1973, Fisk et al. 1973). In such models the low energy particles seen at 1-5 A.U. are considered to have been cooled down by adiabatic deceleration from much higher energies. As discussed earlier, such energy loss would produce the $J \cong AT$ type spectra we actually observe. It appears then that we must seek alternative explanations for the observed ^{2}H/^{4}He ratio. In addition the observed ^{4}He spectrum is very much flatter than the interstellar spectrum which results from a source spectrum which is a kinetic-energy power law. This implies that we cannot have both small modulation and a ^{4}He source spectrum which is a power law in kinetic energy.

We note in this regard that Fisk (1973) has proposed steep upturns ($j(T) \propto T^{-6.5}$) below ~ 100 MeV per nucleon in both the proton and helium local interstellar spectra in order to account for the flat ^{4}He spectrum observed at earth in 1972. The ^{4}He upturn then reaches rigidities twice those of the proton upturn allowing the ^{4}He upturn to contribute significantly to the intensity at earth while the protons have rigidities sufficiently low to exclude them. In this way a flat ^{4}He spectrum could be accompanied by a low energy proton spectrum with $J \cong AT$ as is observed. Presumably such upturns would result from a nearby source and there would be no corresponding ^{2}H upturn.

It should be kept in mind that Meyer's model (Meyer, 1971) is an equilibrium model where it is assumed that protons and helium nuclei have the same spectral shapes at the source. Even if one relaxes this assumption, <u>it is still difficult to escape the conclusion that one requires a large local population of low energy helium nuclei to produce the small ^{2}H/^{4}He ratios that we observe</u>.

McDonald *et al*. (1974) and Hovestadt *et al*. (1973) have recently reported the existence of a new component of quiet-time low-energy cosmic rays distinguished by an anomalously large oxygen-to-carbon ratio and a spectrum steeply rising towards lower energies. The steepness of the spectrum at low energies also implies origin from a nearby source. Based on these measurements there is a low-energy cosmic-ray component whose dominant constituents are ^{4}He, N and O.

Several hypotheses of possible nearby sources have been advanced. These include the interplanetary acceleration model of Fisk *et al*. (1974) and the nova explosion model of Hoyle and Clayton (1974). Both models predict enhancementsof He, N and O. There undoubtedly exist a wide range of additional possibilities. These observations (i.e. the

$^{2}H/^{4}He$ and $^{3}He/^{4}He$ ratios, the anomalous O/C ratio, and the low energy spectra of O and He) do establish that there must exist a hierarchy of cosmic ray sources in our galaxy. The critical test will come when these measurements can be extended to interstellar space or the distant parts of the modulation region where energy-loss effects are negligible.

FIGURE CAPTIONS

1. a) Histograms showing deuterium resolution of the IMP 7 experiment in various energy intervals. Proton peak is absent in 42.5-53 MeV per nucleon interval since the proton range at this energy exceeds the thickness of the detector.

   b) ^{3}He histograms from the Pioneer 10 experiment in various energy intervals.

2. a) ^{2}H spectra at different times during the last solar cycle.

   b) ^{3}He spectra; solid lines show consistency of data with $J \cong AT$ behavior.

3. a) Comparison of measured ^{2}H spectrum (this work) with calculated interstellar spectra (Meyer 1971) for two extreme assumptions of source spectra.

   b) Comparison of measured ^{3}He spectrum (this work) with calculated interstellar spectra (Meyer 1971) for the same two assumptions.

4. a) Comparison of measured ^{2}H/^{4}He ratio (this work) with calculated interstellar ratio (Meyer 1971) for various assumptions about the source spectrum.

   b) Comparison of measured and calculated ^{3}He/^{4}He ratios.

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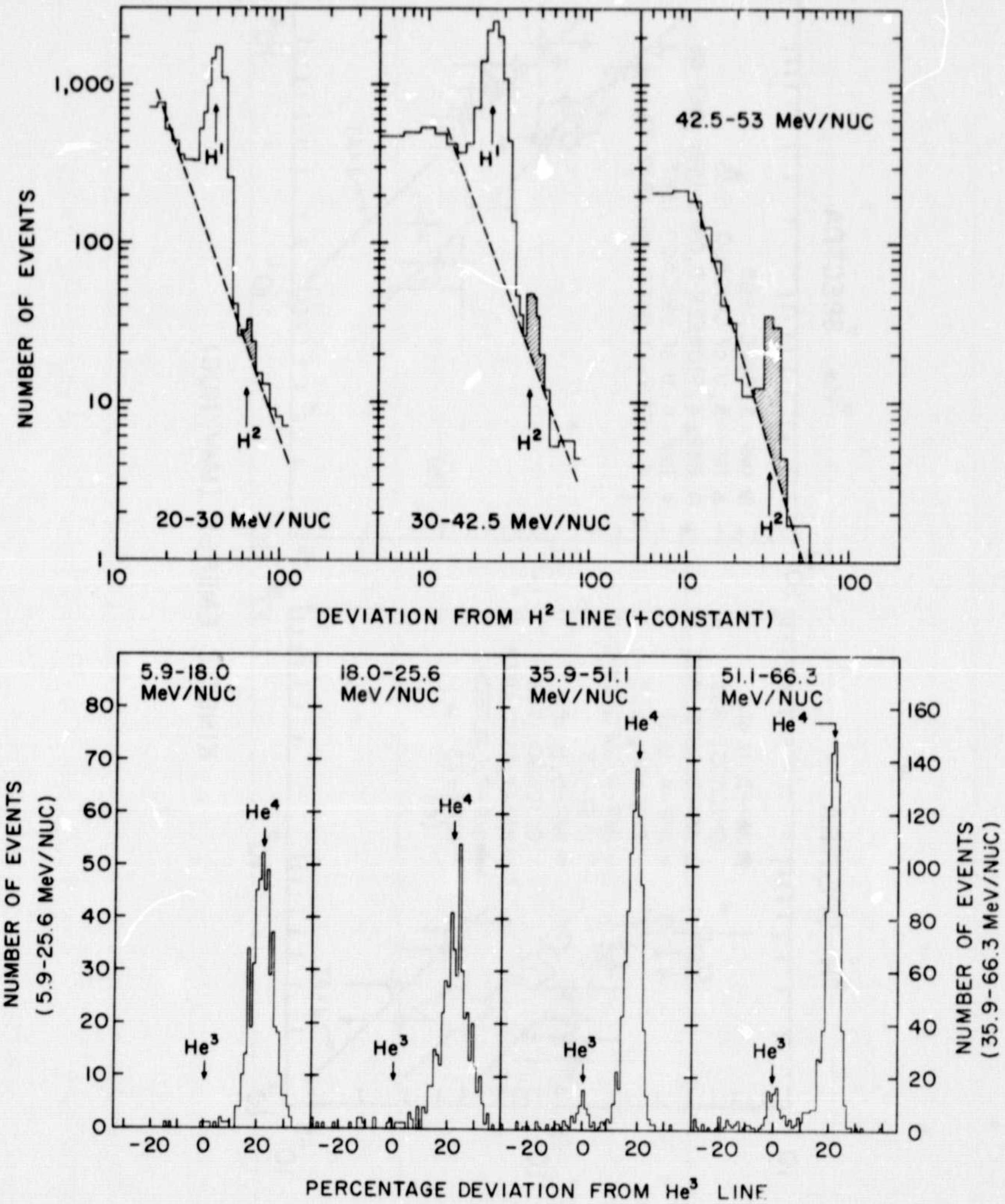

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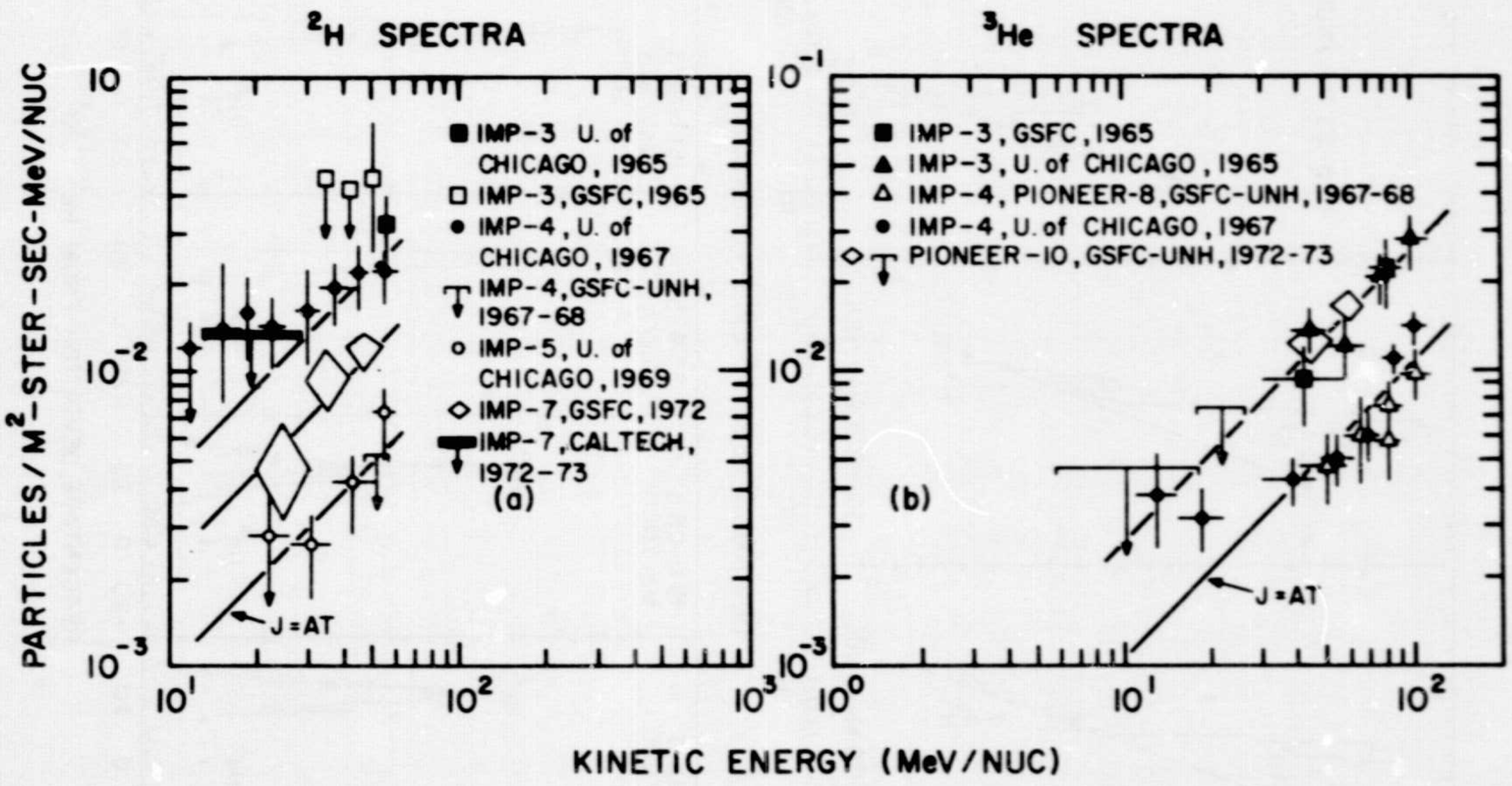

^2H SPECTRA
^3He SPECTRA
PARTICLES/M^2-STER-SEC-MeV/NUC
KINETIC ENERGY (MeV/NUC)
IMP-3 U. of CHICAGO, 1965
IMP-3, GSFC, 1965
IMP-4, U. of CHICAGO, 1967
IMP-4, GSFC-UNH, 1967-68
IMP-5, U. of CHICAGO, 1969
IMP-7, GSFC, 1972
IMP-7, CALTECH, 1972-73
(a)
J=AT
IMP-3, GSFC, 1965
IMP-3, U. of CHICAGO, 1965
IMP-4, PIONEER-8, GSFC-UNH, 1967-68
IMP-4, U. of CHICAGO, 1967
PIONEER-10, GSFC-UNH, 1972-73
(b)
J=AT

CALCULATED INTERSTELLAR SPECTRA (J.P. MEYER, 1971)