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GALACTIC LIGHT ISOTOPES :
SIGNIFICANCE OF THE PRESENT OBSERVATIONS

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All the existing observations which did resolve low energy deuterons and He^3's appear to form a self-consistent set with a hysteresis type of variation over the solar cycle of the ratio $\Phi_d/\Phi_{He^4}{}^*$, where $\Phi_{He^4}{}^*$ is the He^4 flux corrected for the "anomalous" low energy component. This hysteresis can be understood if one accepts (i) an interplanetary deceleration which is weak during the rising phase, and strong during the recovery phase of the solar cycle, and (ii) a continued increase of the escape length from the galaxy below a few GeV/n.

1. The puzzle of the observations of $\Gamma_d \equiv d/He^4$. If one simply plots the points representing all the observations of Γ_d (or even only all the presumably reliable ones) performed around 50 MeV/n between 1965 and 1974, one gets such a mess that I dare not present the picture here. Presumably reliable observations yield ratios ranging between Γ_d = . 30 and .04 which are not monotonically correlated with the degree of solar modulation as measured by the proton or He fluxes. Meanwhile the ratio $\Gamma_{He^3} \equiv He^3/He^4$ remains nicely constant, except for a tendancy to decrease at lower energy (below ≈ 40 MeV/n) after 1972.

Most previous discussions of the observations of deuterons and He^3 were made before 1972 (Ramaty and Lingenfelter 1969 ; Meyer 1970, 1971 ; Comstock et al 1972 ; Ramadurai and Biswas 1974). At that time the limited set of data available was not too conflicting. Only two recent studies have considered most of the data available to-day (Meyer 1974 ; Teegarden et al 1975). They both came to the unpleasant conclusion that the various sets of data are contadictory.

In the present paper we shall try to show that all the observations which did resolve deuterons can be considered as a single self consistent set, and to investigate what can be learnt from this set.

2. Elimination of the He^4 low energy component. It is generally accepted that the flat shape of the He^4 spectrum observed below ≈ 80 MeV/n close to solar minimum 1972 - 74 (and probably in 1965 - 66 as well) cannot be understood in terms of standard theories of solar modulation (interplanetary deceleration) of galactic cosmic rays above 100 MeV/n (Garcia-Munoz et al 1973, 1975 ; Van Hollebeke et al 1973 ; Lockwood et al 1973 ; Fisk 1973). An independant low energy component is probably being observed [1], and this statement will be confirmed in this paper on independant grounds. Whatever their origin, these He^4 nuclei have such low energies that they cannot efficiently produce secondaries before being thermalized (Meyer 1970, 1974)[2].

1. Possibly related with the high N and O (but not C, d, He^3, B) fluxes observed below 30 MeV/n (Hovestadt et al 1973; Mc Donald et al 1974; Fisk et al 1974).
2. The hypothesis of a continuous acceleration of these nuclei during traversal of matter can be rejected on ground of the marked positive slope (≈ E^{+1}) of the deuteron and He^3 spectra.

Hence we shall no longer normalize the deuteron and He^3 fluxes directly to the observed He^4 flux at the same energy/nucleon ϕ_{He^4}, but to the He^4 flux $\phi_{He^4}^*$ which would result from the sole higher energy galactic cosmic ray flux. This flux ϕ_{He^4} can be obtained with reasonable confidence by extrapolation of the fluxes observed above ≈ 80 MeV/n, based on the spectral shapes observed for protons and heavier nuclei, and for He^4 itself close to solar maximum (Hsieh 1970 ; Garcia-Munoz et al 1975 ; Lockwood et al 1973 ; Van Hollebeke et al 1973 ; Rygg et al 1971, 1974 ; Mason 1972), which all agree approximately with the E^{+1} shape predicted for spectra resulting essentially from interplanetary deceleration (Goldstein et al 1970 ; Urch and Gleeson 1972). The correctness of our extrapolation will be checked below.

3. Plot of Γ_d^* and $\Gamma_{He^3}^*$, as a function of the degree of solar modulation .

The ratios $\Gamma_d^* \equiv \phi_d / \phi_{He^4}^*$ and $\Gamma_{He^3}^* \equiv \phi_{He^3} / \phi_{He^4}^*$ corresponding to the various sets of observations are shown in fig. 1 versus the 100 MeV/n He^4 flux at the time of the observation. The latter is apparently not perturbed by any mysterious "Low energy component" and is taken as a measure of the intensity of the solar modulation. For each group of observations, we plot the Γ_d^* corresponding to the highest energy deuteron observation (around 50 MeV/n for most observers) since (i) it is always the most reliable measurement, and (ii) it makes the He^4 flux extraploation from 100 MeV/n least hazardous. We have however indicated by a dashed extension of some error bars the limits on Γ_d^* yielded by reasonably reliable lower energy measurements. The $\Gamma_{He^3}^*$ is taken at the same energy/nucleon as the Γ_d^*, i.e. usually around 50 MeV/n.

The Caltech 1973-74 points however pose a particular problem. The Caltech instrument observes deuterons only up to 27 MeV/n, and He^4 up to 50 MeV/n. The observed He^4 fluxes values are ≈ 60 % higher than those observed by the Chicago group at the same epoch (Stone 1975, Garcia-Munoz et al 1975), but the slightly positive slope of the spectrum permits rejecting the hypothesis of a solar flare contamination. Further the long term stability of the "quiet time" low energy He^4 flux between 1972 and 1974 is impressive (Garcia-Munoz et al 1975). A systematic error in the assignement of the absolute fluxes in one of the instruments seems the only way out. Since the Chicago He^4 fluxes have been used to trace the degree of solar modulation over several years, we shall adopt their 1973-74 values as a standard permitting meaningful comparison[1].

Hence we shall take at face value the Γ_d and Γ_{He^3} ratios measured by the Caltech group, but we shall associate them with the He^4 spectra observed by Chicago in 1973-74 for choosing both ϕ_{He^4} (100 MeV/n) and the correction factor $\phi_{He^4}^*/\phi_{He^4}$ for extrapolation of the He^4 flux down to 27 MeV/n. But it is clear that this interpretation of Caltech's data is only tentative.

4. Analysis of Γ_d and Γ_{He^3} as a function of the degree of solar modulation

Let us now analyze the picture obtained in fig. 1.

Plublished data on He^3 are comparatively scanty. Points in 1969 and 1971 are missing. However the available data do not show any significant deviation from a constancy of $\Gamma_{He^3}^*$ over the solar cycle. This is just a check that we have reasonnably extrapolated the He^4 fluxes observed above 80 MeV/n to get $\phi_{He^4}^*$ at lower energies.[2]

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1. Note also the good agreement between Chicago 1972 He^4 fluxes with those of the Goddard and New-Hampshire groups (Garcia-Munoz et al 1973 , 1975 ; Van Hollebeke et al 1973 ; Lockwood et al 1973).
2. Since the interstellar ratio Γ_{He^3} is not expected to vary with energy between 100 and 500 MeV/n (see fig. 2 below, or Meyer 1971, 1974). Further we do not expect the difference in A/Z between He^3 and He^4 to lead to drastic changes of $\Gamma_{He^3}^*$ at earth over the solar cycle.

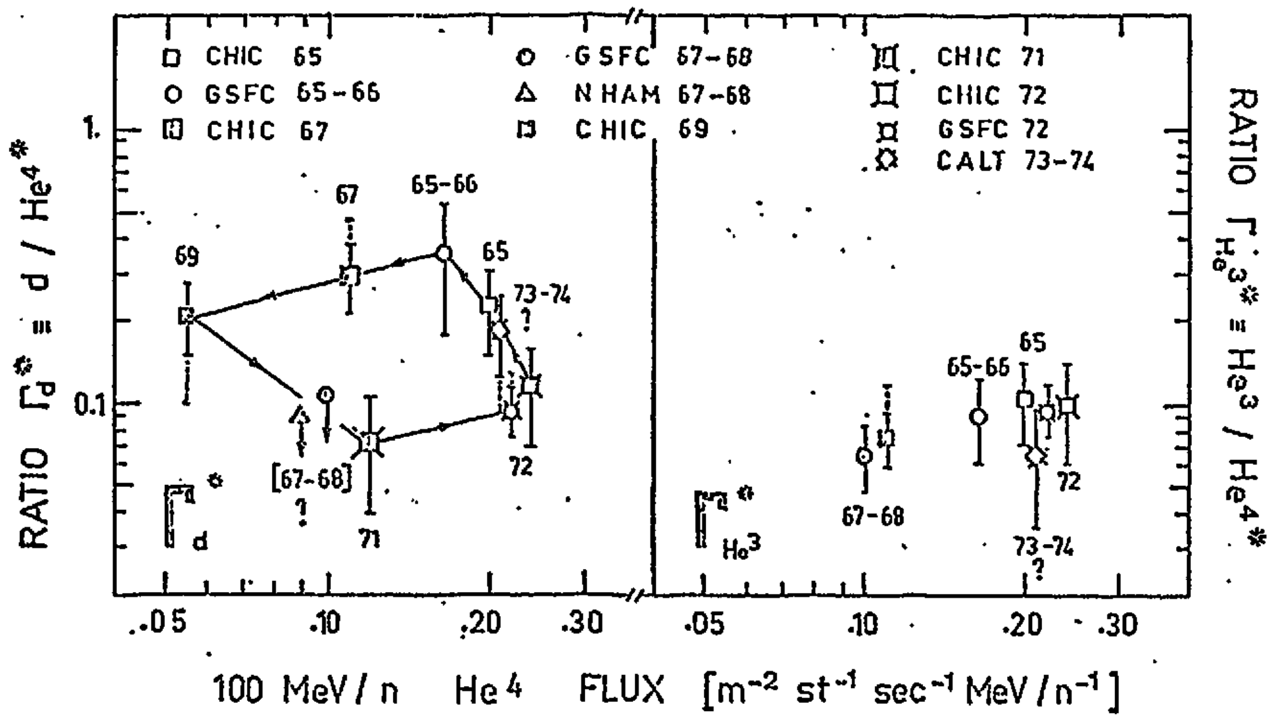

Fig. 1 : The ratios $\Gamma_d^* \equiv \phi_d / \phi_{He}4^*$ and $\Gamma_{He}3^* \equiv \phi_{He}3 / \phi_{He}4^*$, where $\phi_{He}4^*$ is the He^4 flux corrected for the "anomalous" low energy component, vs. $\phi_{He}4$ at 100 MeV/n. Each point Γ^* represents the highest energy measurement of a set of data (usually ≈ 50 MeV/n), which is the best one. Dashed continuations of error bars indicate the tendancy of the lower energy points. The He^3 points have been taken at the same energy/nucleon as the corresponding deuteron points. The deuteron data are from : Hsieh and Simpson 1969 ; Hsieh et al 1971; Baity et al 1971; Meyer 1974 ; Simpson 1974 ; Teegarden et al 1975 ; Stone 1975. He^3 data : Meyer et al 1968 ; Hsieh and Simpson 1969, 1970 ; Hsieh 1970; Baity et al 1971 ; Garcia-Munoz et al 1975 ; Teegarden et al 1975 ; Stone 1975. He^4 data : Hofmann and Winckler 1967 ; Hsieh 1970 ; Hsieh et al 1971 ; Baity et al 1971 ; Lezniak and Webber 1971 ; Mason 1972 ; Van-Hollebeke et al 1973 ; Lockwood et al 1973 ; Garcia-Munoz et al 1973, 1975.

We now consider deuterons. We note that there is only one significant discrepancy in Γ_d^* between observations performed at about the same epoch : that between the clear positive observation of CHIC 67 and the upper limits of GSFC/NMAM 67-68, which did not resolve deuterons. We choose to believe the positive observation, which also fits better with the other observations at neighbouring epochs.

Further, the data taken before and after the solar maximum 1969-70 do show significant differences which in our opinion are too large to be questioned on observational grounds. We therefore take the point of view that the differences are real, and that all the data which did resolve deuterons are consistent with a hysteresis of the ratio Γ_d^* over the last solar cycle : the ratio is as high as .30 ± .10 in the rising phase (1966-1967) and falls to .10 ± .03 in the recovery phase (1971-72) with transition periods at solar maximum and solar minimum. The point of CALT 73-74 suggests a tendency to get back to the 1965 ratio after 1972. But in view of the complicated procedure leading to this estimate of Γ_d^* this latter statement should not be taken too seriously.

5. Significance of the hysteresis on Γ_d^*.

What is the meaning of this hysteresis, if real ? Since d and He^4 have the same A/Z ratio, they are extremely likely to be modulated and in particular decelerated alike. Hence the ratio Γ_d^* among the nuclei below 60 MeV/n at earth is roughly equal to that same ratio Γ_d in interstellar space, averaged over the range of energies

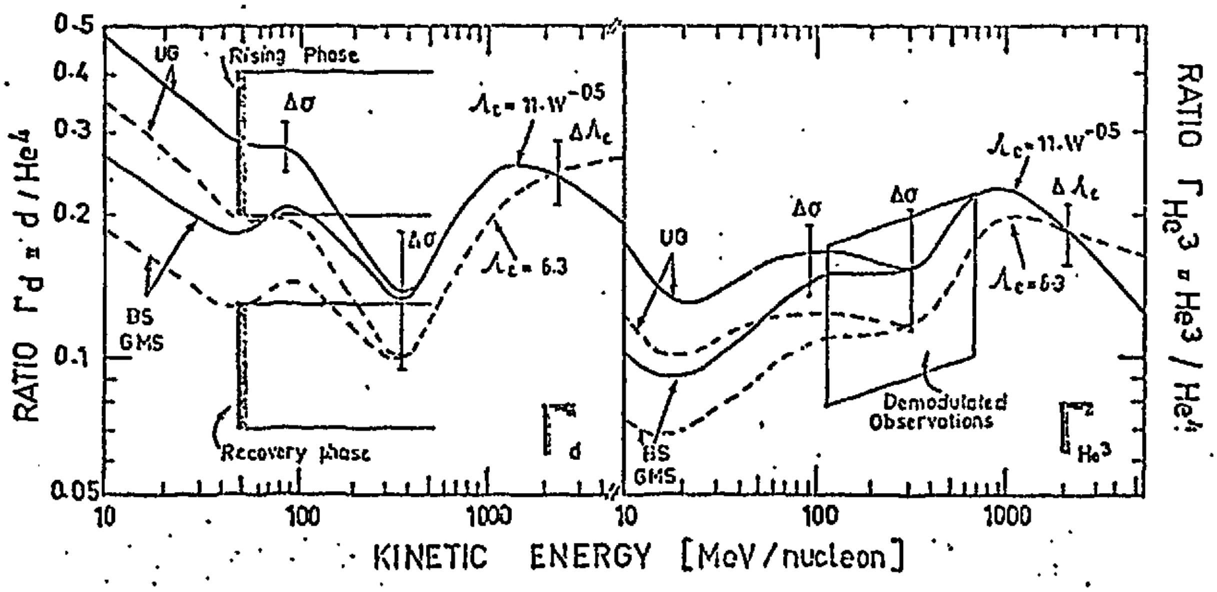

Fig. 2 : Calculated ratios Γ_d and $\Gamma_{He}3$ in interstellar space for a leaky box model with escape lengths Λ_e = 6.3 g cm^{-2}(dashed) and Λ_e = 11.W$^{-0.5}$ (full). (Juliusson et al 1975). The couples of p and He^4 interstellar spectra are those of Urch and Gleeson 1972 (UG) and of Burger and Swanenburg 1971 (BS) and Garcia-Munoz et al 1975 (GMS) (almost identical). The errors associated with the cross sections ($\Delta\sigma$) and with the estimate of the gramage at 2 GeV/n ($\Delta\Lambda_e$) are indicated. For deuterons we have indicated the range of the observations of Γ_d^* at earth near 50 MeV/n during the rising and the recovery phases of the solar cycle (fig. 1). For He^3 we give the range in which all the demodulated observations fit according to a rough estimate by Meyer (1974).

from which the bulk of these nuclei have been decelerated. If the ratio Γ_d in interstellar space is energy dependant in the few hundred MeV/n range, then a change of Γ_d^* at earth can be interpreted in terms of a change of interplanetary deceleration. Hence, we now discuss the interstellar situation, based on interstellar propagation calculations discussed at length in Meyer (1970,1971,1974).

To start with, we note that the hypothesis of identical source (and hence interstellar) spectra expressed in kinetic energy/nucleon for p and He^4 is clearly conflicting with all p and He^4 observations interpreted in terms of realistic models of solar modulation (Webber and Lezniak 1974 ; Urch and Gleeson 1972 ; Burger and Swanenburg 1971 ; Garcia-Munoz et al 1975) : the He^4 source spectrum clearly rises faster then the proton spectrum towards lower energies, and could certainly not be as flat as a total energy power law. Urch and Gleeson (1972) , Burger and Swanenburg (1971) and Garcia-Munoz et al (1975) have proposed realistic couples of p and He^4 spectra, the two latter ones being virtually identical, and somewhat richer than the first one in lower energy particles.

Fig. 2 shows the calculated interstellar ratios Γ_d and $\Gamma_{He}3$ for the above mentioned plausible couples of p and He^4 spectra (after Meyer 1974). An exponential potential pathlength distribution has been assumed, with two different hypothesis on the escape length Λ_e : (i) an energy independant Λ_e = 6.3 g cm^{-2} below a few GeV/n, as suggested by the comparison of the bulk of the observations of heavier nuclei around ≈ 2 GeV/n with the low energy data of Cartwright (1973), and (ii) a Λ_e increasing towards lower energies as Λ_e = 11.W$^{-0.5}$g cm^{-2}, where W is the total energy/nucleon (in GeV/n), a conservative extrapolation towards lower energies of the law obtained by Juliusson et al (1975) between 100 and 2.5 GeV/n (see also Webber et al 1973). We recall that even in the GeV/n range Λ_e is not known to better than ± 20%.

We wish to recall at this point that the rise of the calculated Γ_d between 400 and 100 MeV/n is due to the predominance of the wide "deuteron line" yielded by the $p+p \to d + \pi^+$ process, whose nuclear physics is extremely well known (Meyer 1972). Hence the small error associated with the cross sections close to 100 MeV/n.

We have also plotted, with generous error bars, the extreme ratios Γ_d^* "observed" at earth below 60 MeV/n during the rising and the recovery phases of the solar cycle (see fig. 1), which should be equal to the interstellar ratio Γ_d in some higher energy range depending on the interplanetary deceleration. For He^3, we have just indicated the "observationnal" interstellar Γ_{He^3}, roughly estimated from the observation at earth taking into account the fact that $A/Z(p) < A/Z(He^3) < A/Z(He^4)$ (Meyer 1974).

From fig. 2 we see that, whatever model we take, the He^3 data are accounted for within the large errors associated with both the observations and the demodulation procedure.

As for deuterons, it is seen that the somewhat flatter interstellar spectra of Urch and Gleeson (1972) are more comfortable than the steeper ones of Burger and Swanenburg (1971) and Garcia-Munoz et al (1975) in accounting for the change of Γ_d^* over the solar cycle. For $\Lambda_e = 6.3$ g cm^{-3} we account well for the low Γ_d^* observations, but are extremely marginal for the higher values (especially if the interplanetary deceleration is not negligible in 1967). For $\Lambda_e = 11 \cdot W^{-0.5}$ we can probably account for the high values , but fall too high for the lower ones. However at 400 MeV/n the error associated with the cross sections is quite larger (Meyer 1972, 1974) (and almost uncorrelated with the error at 100 MeV/n). Hence if the 400 MeV/n cross section for deuteron production in p-He^4 interactions lies close to the lower end of the error bar given in Meyer (1972), all the observations which did resolve deuterons can be accounted for provided the escape length Λ_e increases towards lower energies, f.i. as $\Lambda_e = 11\ W^{-0.5}$.

If this whole picture is correct, it implies (fig. 1) that the interplanetary deceleration was lower in the rising than in the recovery phase of the last solar cycle, and about constant during each of these phases. There is evidence for a transition region at solar maximum (data of CHIC 69) and, though less convincing, at solar minimum (CHIC 65, CALT 73-74).

It is difficult to give estimates of the deceleration, which would be extremely model dependant, especially for the rising phase (fig. 2). Very tentatively we propose a deceleration by 200 to 500 MeV/n in the recovery phase, and by $\lesssim$ 100 MeV/n in the rising phase. The latter figure is somewhat low compared with current estimates of the deceleration for 1967 (Urch and Gleeson 1972, 1973). Remember however that Burger and Swanenburg (1971) fit the observations with essentially no deceleration above 100 MeV/n !

These ideas are not in contradiction with the observation that in their recovery from solar maximum the electron fluxes lag in time behind the lower energy proton and He fluxes, which themselves lag in time behind the higher energy fluxes (Van Hollebeke et al 1973 ; Garcia-Munoz et al 1973, 1975 ; Lockwood et al 1973 ; Webber et al 1973 b ; Burger and Swanenburg 1973 a,b ; Fulks et al 1973 ; Caldwell et al 1975). In particular the low electron fluxes observed in 1972-73 indicate that, even though the low energy proton and He fluxes have reached their level of solar minimum 1965, the deceleration in 1972-73 is still of the order of 260 MeV/n, i.e. much higher than in 1965 (Garcia-Munoz et al 1975 ; Teegarden et al 1975). Such a figure fits well with our requirements.

One final remark should be made : a non exponential shape of the potential pathlength distribution would not help increasing the difference between the interstellar values of Γ_d at 400 and at 100 MeV/n. Indeed , as shown in Meyer (1974), acceptable distribution with reduced very short (and very long) pathlengths (e.g. Shapiro et al 1971) do not affect Λ_d above 100 MeV/n, while distributions enriched in very long (and very short) pathlengths would rather decrease the difference.

6. General independant conclusions from self consistency requirements. Without any external assumption on the interstellar spectra and on the nature of the low energy He^4 flux, the directly observed ratios Γ_d and Γ_{He^3} taken as a self consistent set lead to two model independant conclusions, based on fig. V-19 of Meyer (1974), (or fig. 3 of Meyer 1971) :

(i) The very fact that Γ_d is at some times observed as high as ≈ 30 % implies that the interstellar spectra are strongly flattening off at lower energies (at least above ≈ 100 MeV/n)[1].

(ii) The Γ_d and Γ_{He^3} 's as low as 4 % directly observed in 1972-74 can be accounted for only twofolds. One hypothesis is kinetic energy power law source spectra extending all the way up to high energies and extremely weak deceleration in 1972-74, which is in flat contradiction with the preceding conclusion (i).[2] Hence we are left with the other hypothesis : the independant low energy component assumed at the beginning of this paper, which is thus required by the deuteron (and He^3) observations themselves.

7. Conclusions. The complete set of existing measurements which did resolve deuterons and He^3 is highly suggestive of a hysteresis of the ratio Φ_d/Φ_{He^4}* over the last solar cycle. This hysteresis can be accounted for in terms of interstellar propagation and interplanetary deceleration (assuming realistic proton and He interstellar spectra) if one accepts :

- an interplanetary deceleration which is weak during the rising phase of the solar cycle (very tentatively $\lesssim 100$ MeV/n for A/Z = 2 nuclei), stronger during the recovery phase (200 to 500 MeV/n).
- a continued increase of the escape length Λ_e from the galaxy below a few GeV/n.

Further, the data taken as a consistent set

- permit an independant rejection of steep interstellar spectra above ≈ 100 MeV/n
- require independently the presence of a low energy He^4 component, not associated with the deceleration of higher energy nuclei.

References

Baity, W.H., et al. 1971, Ap. J. 164, 521
Burger, J.J., et al. 1971, 12th ICCR, Hobart, 5, 1858
Burger, J.J., et al. 1973 a, J. Geophys. Res. 78, 292
Burger, J.J., et al. 1973 b, 13th ICCR Denver, 5, 3106
Caldwell, J.,et al. 1975, 14th ICCR, Munich
Comstock, G.M., et al. 1972, Ap. J. 173, 691
Fisk, L.A., 1973, Bull. Am. Phys. Soc. 18, 654
Fisk, L.A., et al., 1974, Ap. J. (Letters) 190, L 35
Fulks, G., et al., 1973, 13th ICCR, Denver, 2, 753
Garcia-Munoz, M., et al., 1973, 13th ICCR, Denver, 2, 1304
Garcia-Munoz, M., et al., 1975, Preprint U. of Chicago EFI 75-10
Goldstein, M.L., et al. 1970, Phys. Rev. Letters 25, 832
Hofmann, D.J., et al. 1967, Planet. Space Sci. 15, 715
Hovestadt, D., et al. 1973, Phys. Rev. Letters 31, 650
Hsieh, K.C., 1970, Ap. J. 159, 61
Hsieh, K.C., et al. 1971, Ap. J. 166, 221
Hsieh, K.C. et al., 1969, Ap.J. Letters, 158, L 37
Hsieh, K.C., et al., 1970, Ap. J. Letters, 162, L 197
Julliusson, E., et al. 1975, 14th ICCR, Munich.
Lezniak, J.A., et al. 1971, J. Geophys. Res. 75, 1605
Lockwood, J.A., et al. 1973, 13th ICCR, Denver, 5, 3139
Mason, G.M. 1972, Ap. J. 171, 139
Mc Donald, F.B., et al. 1974, Ap. J. Letters 187, L 105
Meyer, J.P., 1970, Ap. Letters, 7, 61
Meyer, J.P., 1971, 12th ICCR, Hobart, 7, 2565
Meyer, J.P., 1972, Astron. Ap. Suppl. 7, 417
Meyer, J.P., 1974, Ph.D. Thesis, Université de Paris, Orsay
Meyer, J.P., et al., 1968, Can. J. Phys. 46, S 503
Ramadurai, S. et al., 1974, Ap. Sp. Sci. 30, 187
Ramaty, R., et al., 1969, Ap. J. 155, 587
Rygg, T.A., et al.,1971, J. Geophys. Res. 76, 7443
Rygg, T.A., et al.,1974, J. Geophys. Res. 79, 4127
Shapiro, M.M., et al., 1971, 12th ICCR, Hobart, 1, 221
Simpson, J.A. 1974, private communication
Stone, E.C., 1975, Private communication
Teegarden, B.J., et al., 1975, Preprint NASA/GSFC
Urch, I.H., et al., 1972, Ap. Sp. Sci. 17, 426
Urch, I.H., et al., 1973, Ap. Sp. Sci. 20, 177
Von Rollebeke, M.A.I., et al. 1973, 13th ICCR, Denver, 2, 1298
Webber, W.R.,et al., 1974, Ap. Sp. Sci. 30, 361
Webber, W.R., et al., 1973 a, 13th ICCR, Denver, 1, 248
Webber, W.R., et al., 1973 b, 13th ICCR, Denver, 2, 760

1. We exclude the hypothesis that solar modulation could be different for d and He^4 at the same energy/nucleon.
2. Not to speak of the 1972-1973 electron observations, which are interpreted as implying a deceleration of ≈ 260 MeV/n for A/Z = 2 nuclei (Webber et al 1973 b ; Burger and Swanenburg 1973 a, b ; Fulks et al 1973 ; Caldwell et al 1975 ; Garcia-Munoz et al 1975 ; Teegarden et al 1975).