of Warburton *et al.*[19] In the case of the 6.44-MeV level a branch to the 3.95-MeV level was suspected[20] and confirmed[21] as well as a branch to the 5.10-MeV level. The present results are in agreement on the nature of the branching but the low-energy branch is slightly weaker and the ground-state branch slightly stronger in the present results. Recent work[19] on the 7.03-MeV level has indicated a weak ($9\pm5\%$) branch to the 3.95-MeV state which is not seen here. However, a branch of as much as 5% is not ruled out by the present results.

The major portion of the gamma-ray decay of the two levels at 8.49- and 8.96 MeV is observed to be the same here as in previous work.[8] However, a weak branch (about $\frac{1}{6}$) of the 8.49-MeV level to the 5.83-MeV level was not observed here. The gamma radiation from the unresolved pair of levels at 8.96 and 8.99 MeV is attributed to the 8.96-MeV member because of its known[8] gamma-decay branching.

[19] E. K. Warburton, J. S. Lopes, R. W. Ollerhead, A. R. Poletti, and M. F. Thomas, Phys. Rev. **138**, B104 (1965).
[20] H. J. Rose, Nucl. Phys. **19**, 113 (1960).
[21] E. K. Warburton, J. W. Olness, D. W. Alburger, D. J. Bredin, and L. F. Chase, Phys. Rev. **134**, B338 (1964).

The observation in the present experiment of gamma decay from these levels, which are unbound to proton decay, argues that the proton width must be less than or comparable to the gamma width. A comparison of the coincident yield in Fig. 6 with the noncoincident yield[9] shows that there is a noticeable reduction, in the coincident yield, of the relative height of the peaks corresponding to the unbound levels. The proton and gamma widths are, therefore, comparable. They are of the order of 0.01 eV in each case since these are the previously found[8] gamma widths, approximately. Although these values will need modification, since it was assumed[8] that the gamma widths were much less than the proton widths, they will still be of this order of magnitude.

Particle decay of the 8.49- and 8.96-MeV levels requires $l=4$ and $l=5$ proton waves, respectively. The penetrability of such high angular-momentum proton waves is sufficiently low that the proton widths of these levels could be of the above order of magnitude. The total widths of these states are not known, but their upper limits of <0.21 keV and <1 keV for the 8.49- and 8.96-MeV levels, respectively, are certainly consistent with the above very small proton widths.

PHYSICAL REVIEW VOLUME 148, NUMBER 3 19 AUGUST 1966

Neutrons from Deuteron Breakup on He^3

R. G. KERR
*University of Wisconsin, Madison, Wisconsin**
(Received 24 March 1966)

Neutron spectra produced by bombarding He^3 with deuterons have been measured for bombarding energies from 7 to 12 MeV and neutron emission angles from 0 to 70 deg. The observed spectra exhibit no structure attributable to a state in Li^4. An upper limit for the cross section for forming such a state is deduced.

INTRODUCTION

NEUTRON spectra produced when He^3 is bombarded with deuterons were investigated. The existence of neutrons from deuteron breakup on He^3 was first reported by Henkel *et al.*[1] for energies slightly above threshold. Rybakov *et al.*[2] have published a neutron spectrum taken at 18.6-MeV bombarding energy.

The present experiment was undertaken to study the energy distribution of the breakup neutrons as a function of bombarding energy and emission angle, and to search for a possible analog state in Li^4 to the excited states in the α particle.[3,4]

Most experimental searches for Li^4 have been either inconclusive or unsuccessful. A particle-stable Li^4 almost certainly does not exist.[5–8] Unbound states in

* Work supported in part by the U. S. Atomic Energy Commission.
[1] R. L. Henkel, J. E. Perry, Jr., and R. K. Smith, Phys. Rev. **99**, 1050 (1955).
[2] B. V. Rybakov, V. A. Sidorov, and N. A. Vlasov, Nucl. Phys. **23**, 491 (1961).
[3] H. W. Lefevre, R. R. Borchers, and C. H. Poppe, Phys. Rev. **128**, 1328 (1962); C. H. Poppe, C. H. Holbrow, and R. R. Borchers, *ibid.* **129**, 733 (1963).
[4] Additional references may be found in the following articles: He^4 states—W. E. Meyerhof, Rev. Mod. Phys. **37**, 512 (1965) and Ref. 13; Li^4 states—T. A. Tombrello, Phys. Rev. **138**, B40 (1965).
[5] R. K. Sheline, Phys. Rev. **87**, 557 (1952).
[6] H. Tyrén and P. A. Tove, Phys. Rev. **96**, 773 (1954).
[7] S. Bashkin, R. W. Kavanagh, and P. D. Parker, Phys. Rev. Letters **3**, 518 (1959).
[8] W. L. Imhof, F. J. Vaughn, L. F. Chase, Jr., H. A. Grench, and M. Walt, Nucl. Phys. **59**, 81 (1964).

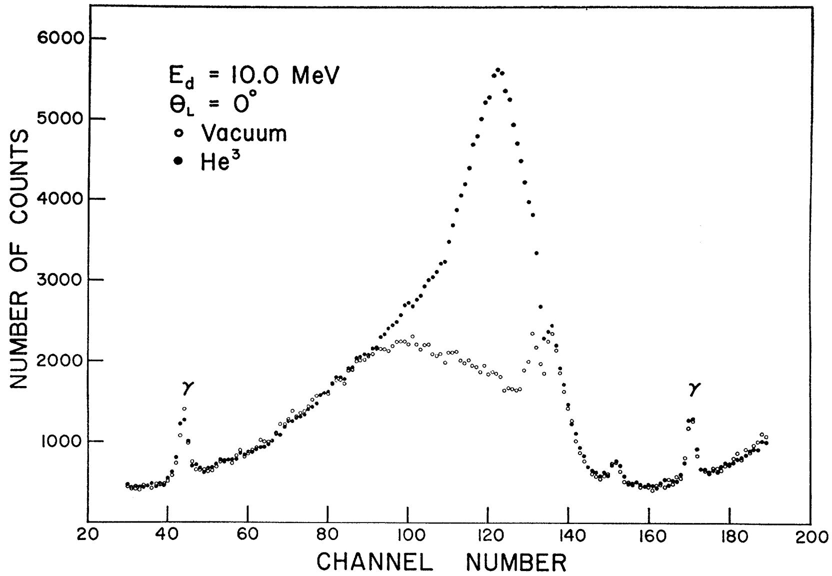

FIG. 1. Typical time-of-flight neutron spectra. This is a composite of foreground (solid circles) and background (open circles) taken at a deuteron energy of 10 MeV and with a 3.0-m flight path. Neutron energy increases to the right. The time between the two γ peaks is 250 nsec and zero time is in about channel 176.

Li^4 have been looked for with varying degrees of success.[9–15]

EXPERIMENTAL

Deuterons were accelerated by a tandem accelerator and neutron spectra were obtained by the pulsed beam time-of-flight method. Details of the spectrometer and experimental procedure have been previously described.[3,16]

Neutrons were detected by a liquid scintillator viewed by an Amperex 58AVP photomultiplier tube. A three-meter flight path was used. The spectrometer had a resolution of about 1.2 nsec/m. Pulse-shape discrimination was used to discriminate against γ rays. The discriminator was set to let a small number of γ rays into the analyzer for time-calibration purposes.

The efficiency of the detector as a function of neutron energy was obtained by measuring the zero-degree yield of the monoenergetic neutrons from the $T(p,n)He^3$ and $D(d,n)He^3$ reactions in a manner previously described.[3] Background subtractions and cross-section calculations were performed by a digital computer. Background spectra were taken at all bombarding energies and observation angles. Neutrons not coming directly from the target showed no time correlation. The region around channel 160 in Fig. 1 is a measure of this flat background taken with a brass shadow cone between the target and the detector. An average over ten channels in this region was subtracted from both foreground and background spectra.

The He^3 was contained in a cylindrical gas cell 2.2 cm long by 0.8 cm diam. Two atmospheres of He^3 were used for foreground runs. Background runs were taken with the cell evacuated. The deuteron beam entered the gas target through a 1.1-mg/cm² nickel foil and exited through an identical foil into an evacuated backstop where it was stopped by 0.5-mm-thick gold. This backstop could be shielded from the detector for observation angles of 10° or greater.

The He^3 gas had an isotopic purity of 99.6% and a chemical purity of 99.8%, the remaining 0.2% being nitrogen and oxygen. No evidence for neutrons from the small amounts of nitrogen and oxygen was observed. Since the breakup spectra from deuteron bombardment of He^4 are very similar[3] to those observed in the present investigation, the effect of the He^4 impurity was not important.

Neutron spectra were collected for deuteron bombarding energies at the center of the gas target from 7 to 12 MeV in 1-MeV steps, and for laboratory neutron emission angles of 0°, 10°, 20°, and 30° for each bombarding energy. At 9-MeV-deuteron energy, additional spectra were determined for angles up to 70°.

RESULTS

Figure 1 shows typical foreground and background spectra. The background spectrum exhibits a broad maximum characteristic of deuteron breakup on the foils and backstop. The spectrum taken with He^3 in the

[9] M. J. Beniston, B. Krishnamurthy, R. Levi Setti, and M. Raymund, Phys. Letters **13**, 553 (1964).
[10] R. L. Dangle, J. Jobst, and T. I. Bonner, Bull. Am. Phys. Soc. **10**, 422 (1965).
[11] G. J. Igo and W. T. Leland, Bull. Am. Phys. Soc. **10**, 1193 (1965).
[12] R. W. Zurmühle, Nucl. Phys. **72**, 225 (1965).
[13] J. Cerny, C. Détraz, and R. H. Pehl, Phys. Rev. Letters **15**, 300 (1965).
[14] D. Boyd, P. F. Donovan, J. V. Kane, J. F. Mollenauer, and P. Parker, Bull. Am. Phys. Soc. **11**, 9 (1966).
[15] R. W. Kavanagh and P. D. Parker, Phys. Rev. **143**, 779 (1966).
[16] H. W. Lefevre, R. R. Borchers, and C. H. Poppe, Rev. Sci. Instr. **33**, 1231 (1962).

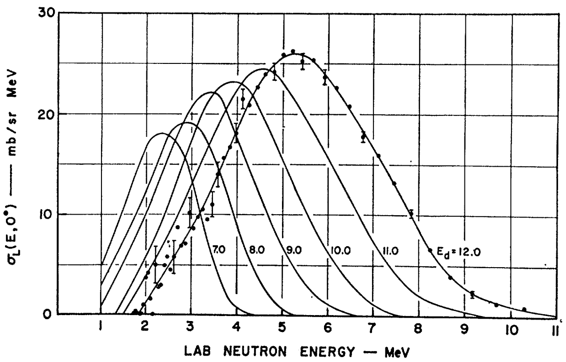

FIG. 2. Zero-degree yield of neutrons from the $He^3(d,np)He^3$ reaction in the laboratory system. E_d is the deuteron energy in MeV at the center of the target. The lines in Figs. 2–5 are smooth curves drawn through the data.

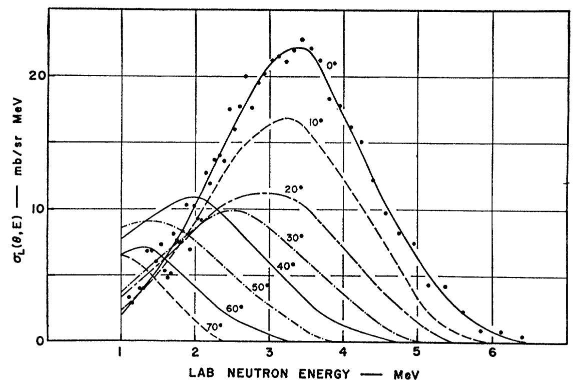

FIG. 4. Angular distribution of the $He^3(d,np)He^3$ neutron spectrum for a bombarding energy of 9 MeV.

target cell follows the background spectrum very closely at low energies (channels 50 to 90 in Fig. 1) and at higher energies exhibits an additional broad peak.

Neutrons from the $C^{12}(d,n)N^{13}$ reactions were observed in all the spectra. These were due to small amounts of carbon on the foils and backstop assembly. Since these neutrons could be readily identified and appeared equally in foreground and background spectra, they caused no difficulty in the analysis. The peaks caused by neutrons from carbon occur in channels 131, 136, and 152 in Fig. 1.

Figures 2 and 3 show the variation with bombarding energy of the 0° neutron spectra in the laboratory and center-of-mass systems. For clarity, data points are shown for 12 MeV only. The error bars include only statistical uncertainties. The spectra have been cut off below 1-MeV laboratory energy because of poor statistical accuracy and rapidly changing detector efficiency. The present data agree with those of Rybakov *et al.*[2] in the general shape of the spectra and the absence of narrow peaks.

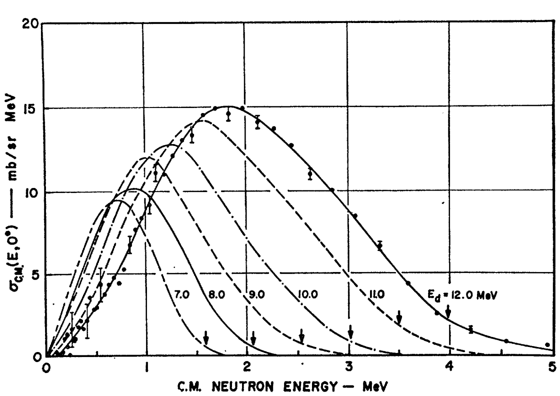

FIG. 3. Zero-degree yield of neutrons from the $He^3(d,np)He^3$ reaction in the center-of-mass system. The arrows indicate the maximum possible neutron energy for each bombarding energy. The apparent neutron yield beyond the arrows can be accounted for by the time spread introduced by the spectrometer.

Figure 4 shows the neutron energy spectra obtained at a bombarding energy of 9 MeV as a function of angle in the laboratory system. Figure 5 shows the variation of center-of-mass cross section with center-of-mass angle for the production of 1-MeV neutrons at a deuteron bombarding energy of 9 MeV. Since at this bombarding energy the most probable neutron energy is 1 MeV, the smallest statistical uncertainty is obtained at this energy. The error bars give the statistical uncertainties and are based on the total number of counts between 0.9 and 1.1 MeV. The angular distributions of neutrons with other energies have the same general shape, but for neutrons with lower energies the ratio of the zero-degree yield to the yield at larger angles is smaller than that shown in Fig. 5, while for higher energy neutrons the ratio is greater. At other bombarding energies the angular distributions have the same general shape as shown in Fig. 5 although data were taken only for angles up to 30°.

The spectra in Fig. 2 have been integrated over neutron energy to obtain the differential cross sections shown in Fig. 6. This figure also contains the results of Henkel *et al.*[1] and Rybakov *et al.*[2] There is a discrepancy of about a factor of 2 between the present data and those of the previous experiments. The same dis-discrepancy was found by Lefevre *et al.*[3] for the $He^4(d,np)He^4$ reaction. The reason for this difference is not known.

The over-all estimated uncertainty in the absolute cross sections is about 20% and is mainly due to background subtraction, uncertainties in the detector efficiency, and counting statistics.

DISCUSSION

Possible neutron-producing reactions from the bombardment of He^3 with deuterons are the following:

$$He^3+d \to p+p+p+n+n \qquad E_{th}=16.58 \text{ MeV} \qquad (1)$$

$$He^3+d \to p+p+d+n \qquad E_{th}=12.87 \text{ MeV} \qquad (2)$$

$$He^3+d \to Li^4+n \to He^3+p+n \qquad (3)$$

$$He^3+d \rightarrow He^3+p+n \qquad E_{th}= 3.71\text{ MeV}. \quad (4)$$

Neutrons from reactions (1) and (2) would not be observed in the present experiment because of the high thresholds E_{th} of the reactions. Neutrons from reaction (3) should appear as a peak which yields a consistent Q value independent of bombarding energy and observation angle. Neutron spectra from reaction (4) could show contributions from several processes. These are illustrated in Fig. 7. A final-state interaction between the He^3 and proton recoiling with small relative velocity at 180° with respect to the beam direction would appear as a peak in the spectrum at high neutron energies, indicated by the arrow marked "He^3+p" in Fig. 7. The corresponding neutron energies for other bombarding energies are indicated by the arrows in Fig. 3. A final-state interaction between the neutron and proton emitted in the forward direction with small relative velocity would result in a maximum at the energy given by the arrow marked "$p+n$". A final-state interaction between the He^3 and neutron emitted in the forward direction with small relative velocity would appear as a peak at the energy indicated by the arrow marked "He^3+n."

Rybakov *et al.*[2] have suggested that the shape of the neutron spectra from this type of reaction can be explained by the production of particle pairs in states of nonzero angular momentum. The relative angular momentum between the He^3 and proton has the value 1, and the angular momentum between the neutron and the He^3+p center of mass also has the value 1. The calculated shape of the neutron spectrum is that given by the dashed curve in Fig. 7. The solid curve gives the calculated shape of the spectrum when both angular momenta have the value zero. For comparison with the experimental results, both curves in Fig. 7 have had a resolution function folded in, which adds a slight high-energy tail. Delves[17] points out, however, that this formulation holds strictly only at threshold, and that at higher energies there will be contributions from various l values so that cross terms will also contribute to the cross section.

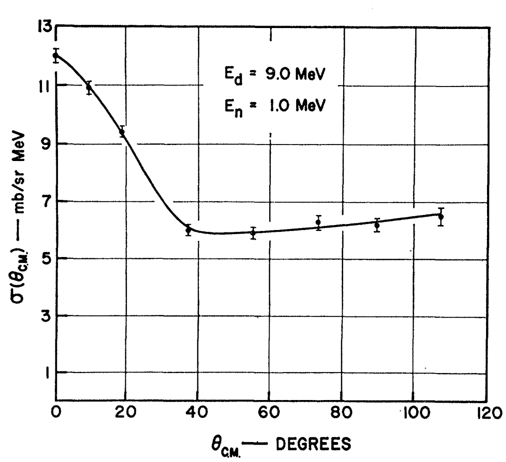

FIG. 5. Center-of-mass cross section as a function of center-of-mass angle for a bombarding energy of 9 MeV and neutron energy of 1 MeV. The statistical errors are based on the total number of counts between 0.9- and 1.1-MeV neutron energy.

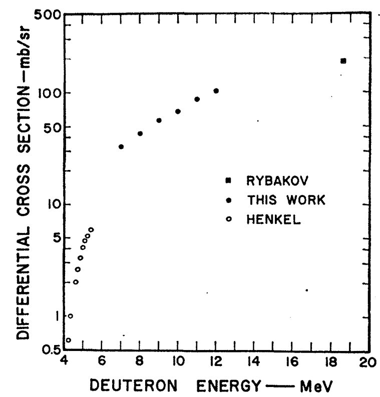

FIG. 6. Zero-degree laboratory differential cross section for the $He^3(d,np)He^3$ reaction. Also shown are the results of Rybakov *et al.* (Ref. 2) and Henkel *et al.* (Ref. 1).

The observed neutron spectra exhibit the following prominent features. There is no evidence for a final-state He^3+p interaction. For deuteron energies up to 10 MeV the high-energy tail beyond the maximum energy arrows in Fig. 3 can be completely accounted for by the time spread introduced by the neutron spectrometer. A small portion of this tail could be due to He^3+p for 11 and 12 MeV. The most probable neutron energy for every spectrum lies between the energy predicted by angular-momentum conditions as shown by the dashed curve in Fig. 7 and that for a final-state $p+n$ interaction as shown by the arrow marked "$p+n$" in Fig. 7. It would appear that both these processes are making some contribution.

If any of the excited states of the α particle has isospin 1, analog states in H^4 and Li^4 should be observed. The excited state in He^4 at about 20 MeV was at one time

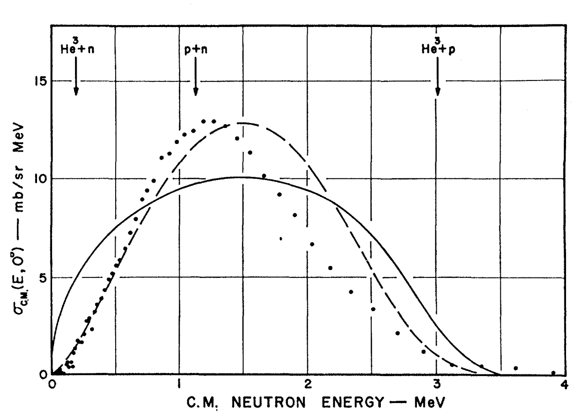

FIG. 7. Zero-degree neutron spectrum in the center-of-mass system for 10-MeV bombarding energy. The curves are explained in the text.

[17] L. M. Delves, Nucl. Phys. 20, 275 (1960).

assigned $T=1$,[18] but it now appears that it probably has isospin 0.[15,19] A second state at about 22 MeV[20–23] probably also has zero isospin.[24] The first $T=1$ state in He^4 has been predicted to lie between 24 and 26 MeV based on results of (p,γ) and photonuclear studies.[24,25]

None of the spectra in the present study exhibit a peak which could be interpreted as a state in Li^4. The cross section for formation of a Li^4 state analog to the 20-MeV state seen in the $T(d,n)He^{4*}$ reaction[3] should be slightly smaller than that for the He^4 state because of the higher Coulomb barrier, but it would not be expected to be an order of magnitude smaller. For a comparison with the He^4 state, the largest cross section for formation of a Li^4 state that would have been observed in the present experiment was computed under the assumption that the peak had to stand out clearly above the breakup spectra. The calculation was made for a bombarding energy of 9 MeV which was the middle of the range of bombarding energies used. The computed upper limit would be smaller for lower bombarding energies and larger for high bombarding energies, but it would be of the same order of magnitude as the calculated value. Since the upper limit also depends upon the width of the level, the calculation was made for three assumed widths. In Table I the width of the excited state in He^4 and the cross section for its formation deduced from the data of Poppe *et al.*[3] for bombarding energies from 5.86 to 7.83 MeV are compared with the upper limit of the cross section for formation of a state in Li^4 compatible with the present results. The values given in Table I give additional evidence for the assignment of isospin 0 to the 20-MeV state in He^4.

Most searches for unbound states in Li^4 have been inconclusive. The possibility of a Li^4 state at about 10.6 MeV in the He^3-p system produced in $_\Lambda He^4$ decay has been reported.[9] However, the existence of such a state has not been verified by the investigation of elastic scattering of protons by He^3.[10,11,14] Nor did an investigation of the $D(He^3,pn)He^3$ reaction by Zurmühle[12] give any evidence for a state in Li^4. A recent paper by Cerny *et al.*[13] reports a broad state in Li^4 which is unbound by about 2.9 MeV to He^3-p decay. This state, observed in the $Li^6(p,t)Li^4$ reaction, has a width of about 5 MeV and a cross section less than 100 μb/sr for angles greater than 15°. The authors claim that this is an analog to a state in He^4 at 22.5 MeV. They arrive at this value by applying a Coulomb correction to their value for the Li^4 mass, and they find an indication of such a state in He^4 by subtracting a rapidly changing background and a narrow peak at 21.4 MeV from a spectrum obtained in the $Li^6(p,He^3)He^4$ reaction. This state in Li^4 is within the energy range investigated in the present experiment, but its reported width is so great and the cross section so small that it would not have been detected in the present study. An analog to a He^4 state between 24 and 26 MeV would probably not have been seen in the present study since it would lie at the upper end of the energy range.

In summary, the neutron spectra produced in the reaction $He^3(d,np)He^3$ give no indication of states in Li^4 in agreement with previous searches for Li^4.

TABLE I. Maximum cross section for formation of a Li^4 state up to 5.0 MeV in the He^3-p system compatible with the present results for various assumed widths.

State	Γ (keV)	$\sigma_{c.m.}(0°)$ (mb/sr)
He^{4*}	300–400	20
Li^4	250	2
	375	3
	500	4

ACKNOWLEDGMENTS

The author would like to thank Professor H. H. Barschall for suggesting this experiment and for his advice and guidance throughout this work. The advice of Professor R. R. Borchers and Dr. R. M. Wood and their assistance with the spectrometer has been invaluable.

[18] C. Werntz and J. G. Brennan, Phys. Letters **6**, 113 (1963).

[19] P. Szydlik and C. Werntz, Phys. Rev. **138**, B866 (1965).

[20] N. A. Vlasov, G. F. Bogdanov, S. P. Kalinin, B. V. Rybakov, and V. A. Sidorov, Proceedings of the International Conference on Neutron Interactions with Nuclei, Columbia University, 1957 (unpublished).

[21] S. Hayakawa, N. Horikawa, R. Kajikawa, K. Kikuchi, H. Kobayakawa, K. Matsuda, S. Nagata, and Y. Sumi, Phys. Letters **8**, 333 (1964).

[22] P. D. Parker, P. F. Donovan, J. V. Kane, and J. F. Mollenauer, Phys. Rev. Letters **14**, 15 (1965).

[23] L. E. Williams, Phys. Rev. Letters **15**, 170 (1965).

[24] W. E. Meyerhof, Bull. Am. Phys. Soc. **10**, 698 (1965) and private communication.

[25] N. A. Vlasov and L. N. Samoilov, At. Energ. USSR **17**, 3 (1964) [English transl.: University of California Radiation Laboratory, Report No. 1183 (unpublished)].