accuracy of 0.01 cm^{-1} in the ionization potential, the isotopic purity of the element has also to be considered. In the case of lithium, where this is most serious, our computations are based on the isotope Li^7. For the naturally abundant element, which contains an admixture of 7.5% of Li^6, the ionization potential becomes uncertain by about 0.7 cm^{-1} due to the isotope effect alone.

It is clear that our method is directly applicable also to the treatment of the excited states of two-electron atoms, including the ortho states. Work is now in progress on the $2\,^1S$, $2\,^3S$, and $2P$ states.

ACKNOWLEDGMENT

I am indebted to Mr. Yigal Accad for assistance in programing.

PHYSICAL REVIEW VOLUME 112, NUMBER 5 DECEMBER 1, 1958

Measurements of the Interaction of 95-Mev Protons with He^4†

W. SELOVE* AND J. M. TEEM‡
Harvard University, Cambridge, Massachusetts
(Received May 26, 1958)

Elastic and inelastic scattering and the (p,d) "deuteron pickup" process have been studied using a proton beam of energy about 95 Mev incident on a liquid helium target. The elastic scattering shows a nuclear-Coulomb interference dip at 9°, a slight diffraction-type minimum at about 57°, and a deep minimum, approximately 10^{-29} cm^2/sterad at 135°. (All angles and cross sections are in the center-of-mass system.) Inelastic scattering spectra were obtained at laboratory angles of 10°, 15°, and 30°. These spectra are characterized by broad peaks, roughly 10-Mev wide, centered around an energy about 6 Mev below the upper kinematical limit for inelastic scattering. Their interpretation is discussed qualitatively both in terms of quasi-elastic nucleon-nucleon scattering and in terms of strong interaction between parts of the dissociated α particle in virtual or continuum states. A minimum was observed in the $He^4(p,d)He^3$ differential cross section at about 29°. Analysis of the (p,d) data at 95 Mev and 32 Mev in the "transparent nucleus" Born approximation yielded inconsistent results; presumably this inconsistency is due to the failure of the model at the lower energy due to the tightly bound structure of He^4.

I. INTRODUCTION

THE interaction of high-energy nucleons with He^4 is of particular interest because with high incident energies, one can expect to study the internal structure of the target nucleus, and the presumed complete space symmetry of the He^4 wave function should simplify the interpretation of the results. At high energies the proton-He^4 interaction can proceed through at least seven channels, from elastic scattering through complete disintegration of the alpha particle. The possible reactions, together with their respective Q values, are listed in Table I.

We hoped when this investigation was begun that by obtaining data on both the elastic differential scattering cross section and the $He^4(p,d)He^3$ "pickup" cross section at a sufficiently high energy, we could deduce an equivalent single-particle wave function for He^4. This purpose might be accomplished as follows: (A) If the elastic scattering is analyzed on the impulse approximation,[1] the total scattering amplitude factors into the product of a nuclear form factor and a sum of nucleon-nucleon scattering amplitudes. The latter sum involves the non-spin-flip parts of the triplet and singlet p-n and p-p scattering amplitudes. If one knew what to insert for these amplitudes, one could then obtain from the experimental data the nuclear form factor—which is equivalent to obtaining the nuclear wave function. (Inversely, of course, if the nuclear wave function were known, one could get information on the nucleon-nucleon scattering amplitudes.) (B) Analysis of the (p,d) pickup data, on the "transparent-nucleus" or

TABLE I. Possible interactions and Q values of high-energy protons with He^4.

Reaction	Q (Mev)	Experimental observation
1. $He^4(p,p)He^4$	0	Elastic scattering
2. $He^4(p,d)He^3$	−18.32	"Pickup" deuterons
3. $He^4(p,2p)H^3$	−19.81	a (Quasi-elastic p-p type)
4. $He^4(p,pn)He^3$	−20.55	a (Quasi-elastic p-n type)
5. $He^4(p,pd)H^2$	−23.75	a, b
6. $He^4(p,2pn)H^2$	−25.97	a, b
7. $He^4(p,2p2n)H^1$	−28.2	a
8. [$He^4(p,p^1)He^{4*}$]	?	Peak on the inelastic proton continuum

[a] Reactions 3, 4, 5, 6, and 7 all contribute to the inelastic proton continuum, with varying "threshold" proton energies roughly equal to the difference between incident proton energy and the appropriate Q value.
[b] Reactions 5 and 6 both contribute to the deuteron continuum with deuteron "threshold" energies roughly less than the peak from reaction 2 by the difference in the Q values (see Fig. 2).

† Assisted by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
* Now at the University of Pennsylvania, Philadelphia, Pennsylvania.
‡ Now at the California Institute of Technology, Pasadena, California.
[1] G. F. Chew, Phys. Rev. 80, 196 (1950).

Chew-Goldberger type Born approximation method,[2,3] should also give an equivalent single-particle wave function for the pickup neutron—that is, a wave function for He^4.

We originally hoped that if we could make good guesses as to how the experimental nucleon-nucleon scattering cross sections should be decomposed into the appropriate partial scattering amplitudes, then we could obtain a wave function from method (A) which would be consistent with that obtained from (B), and we would have information both as to the He^4 wave function and as to the accuracy of the approximation methods used. There was some reason to hope that these approximation methods might indeed give useful results, for both have been used with some degree of success at energies about the same as or less than the energy used here.[3–5] This degree of success has been obtained for nucleons having much less binding than have the nucleons of He^4, it is true, but nevertheless, it was hoped that because He^4 has so few nucleons it might still be amenable to treatment by these methods, which essentially involve the assumption that the incident particle interacts with a single target nucleon at a time, rather than with a cluster.

The inelastic scattering of protons by He^4 is also of interest because of the information that it might provide about possible excited states and about the continuum states of the four-nucleon system. For this reason the inelastic scattering of protons by He^4 has been studied at lower energies[6]; no discrete inelastically scattered proton group corresponding to an excited state in He^4 has been observed. Recent electron-He^4 scattering measurements, however, have suggested that excited states in He^4 may actually exist.[7]

II. EXPERIMENTAL METHOD AND RESULTS

The external proton beam of the Harvard cyclotron, analyzed in energy to a width of about 2 Mev, was scattered from a liquid helium target. The incident proton flux was measured with a Faraday cup, and the scattered particles detected in an eight-scintillation-counter telescope. The scattered protons and deuterons were analyzed in energy and separated as to mass by simultaneous measurement of range and specific ionization. The scattering chamber[8] and counter arrangement[3] have been described in more detail elsewhere. The cryostat and target are shown in Fig. 1. The rate of liquid helium consumption with this system was approximately 250 cc/hr.

The data on elastic scattering at laboratory angles from 5° to 90°, on inelastic scattering from 10° to 30°, and on the scattered deuterons from 6° to 50° were taken[9] at an effective proton energy in the center of the target of about 94 Mev. Additional elastic scattering data at angles up to 170° were taken at an effective beam energy of about 98 Mev. The helium target thickness was measured at $0.32\pm5\%$ g/cm² He (i.e., 4.8×10^{-22} atoms/cm²) during the former run and about 5% less than this value during the latter run, by observing the energy loss of the incident protons in the target. An integral range spectrum of the beam through the target cell was measured first with the target empty and then filled with liquid helium, using the Faraday cup to count the number of protons through various amounts of aluminum absorber. The transmitted intensity was normalized to the number of incident protons as measured with a thin ion chamber in front of the target. The apparent change in range of the protons on filling the target combined with the calculated dE/dx of protons in aluminum and helium yielded the target thickness.

The angular resolution of the defining counter was about $2\frac{1}{2}°$ in the laboratory system. The effective energy resolution of the counting equipment, including incident beam energy spread, straggling, and finite-resolution effects in the range telescope, was about 3 Mev for protons and about 4 Mev for the "pickup" deuterons. Figure 2 shows a typical range spectrum, in this case for deuterons at $22\frac{1}{2}°$ in the laboratory. The

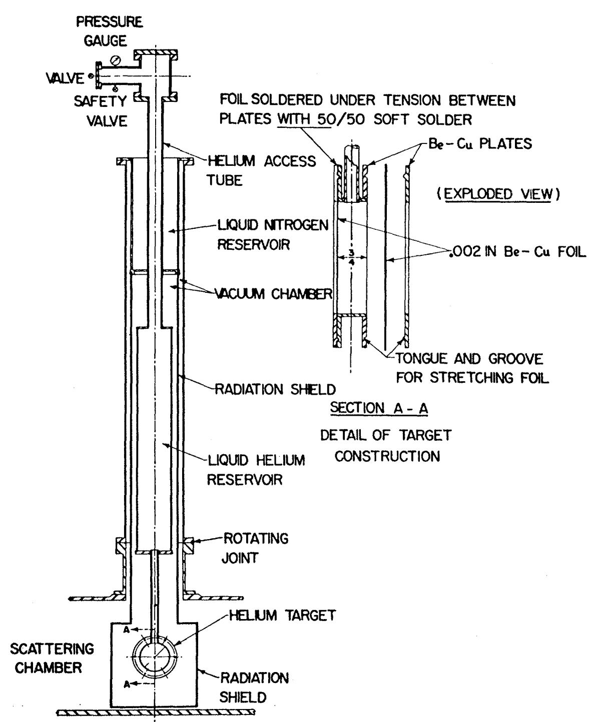

FIG. 1. Liquid helium target and cryostat.

[2] G. F. Chew and M. Goldberger, Phys. Rev. **77**, 470 (1950).
[3] W. Selove, Phys. Rev. **101**, 231 (1956).
[4] S. Glashow and W. Selove, Phys. Rev. **102**, 200 (1956).
[5] O. Chamberlain and M. O. Stern, Phys. Rev. **94**, 666 (1954).
[6] See R. M. Eisberg, Phys. Rev. **102**, 1104 (1956) for work at 40 Mev and references to other work.
[7] R. Hofstadter, Revs. Modern Phys. **28**, 214 (1956).
[8] Kruse, Teem, and Ramsey, Phys. Rev. **101**, 1079 (1956).
[9] These results have been reported briefly previously: Teem, Selove, and Kruse, Phys. Rev. **98**, 259(A) (1955).

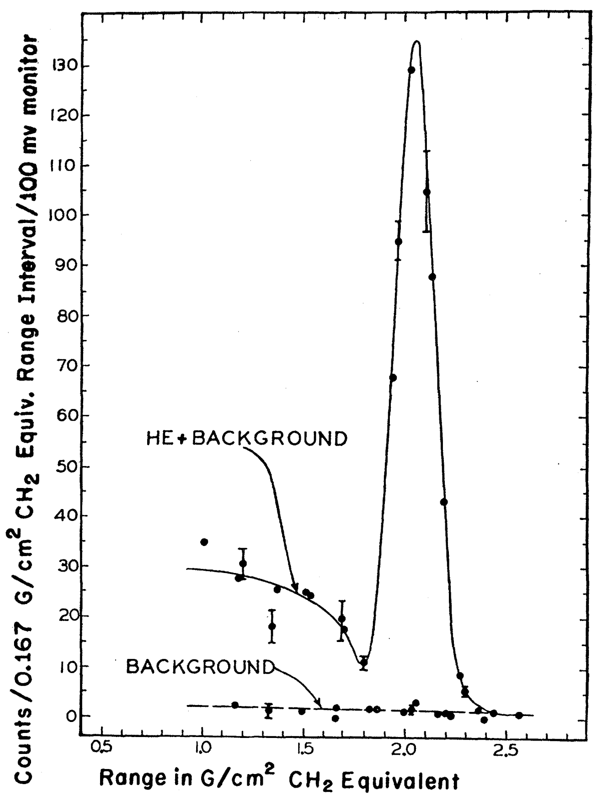

FIG. 2. 94-Mev $He^4(p,d)He^3$: Deuteron range spectrum at $\theta_{lab}=22\frac{1}{2}°$.

separation of the deuterons due to reaction 2, Table I, from those due to reactions 5 and 6 is seen to be unambiguous. In Fig. 3 is shown a typical proton spectrum, in which the range spectrum has been converted into a laboratory cross section, $d^2\sigma/d\Omega dE$, as a function of the laboratory proton energy. The counting rate, analogous to the ordinate of Fig. 2, after subtraction of background from the empty target, has also been corrected for the proton attenuation in the telescope due to nuclear absorption, diffraction scattering, etc.[10] in calculating the cross sections. The errors shown on sample data are those due to counting statistics only. Additional sources of error in the absolute cross sections include estimates of 5% for target thickness, from 2% at the low-energy to 8% at the high-energy end of the spectrum for the attenuation corrections, 1% each from errors in the incident proton flux and solid angle, and up to 3% from uncertainty in the angle of the plane of the target with the incident beam.

By integrating under the elastic peaks, the elastic differential cross section may be calculated. The results, together with their absorption corrections, are tabulated in Table II and plotted semilogarithmically as a function of angle in the center-of-mass system in Fig. 4. Also plotted for comparison are the elastic-scattering results at approximately 30 Mev.[11,12] Similar results of high accuracy have recently been reported on the elastic scattering at 40 Mev.[13] The total elastic scattering cross section (exclusive of the Coulomb contribution) was determined by integration as 73±6 mb. The $He^4(p,d)He^3$ differential cross section can be similarly obtained by integrating under the peak of, for example, Fig. 2. These data have also been corrected for the attenuation of deuterons in the telescope, and the results are shown in Table III and are plotted in Fig. 5, together with the corresponding results at 32 Mev.[14]

The inelastic proton spectra, $d^2\sigma/d\Omega dE$ *versus* proton energy in the laboratory system, obtained at the two other angles are plotted in Figs. 6 and 7. To check for the existence of possible systematic errors, separate symbols are used in plotting the data from each of the four stopping counters. An attempt was made in choosing the absorber values used to overlap these points as much as possible, in order to investigate and eliminate spurious peaks due to possible feed-throughs or counter inefficiencies which could shift counts from

TABLE II. Elastic scattering of protons from He^4 at about 95 Mev. Background has been subtracted; some representative background values relative to the scattered intensities from He^4 were 150% at 9°, 95% at 13°, 40% at 19°, 7% at 28°, 1% at 73°, 60% at 133°, and 35% at 157° (all angles in the c.m. system). The data have been corrected for absorption and scattering in the range telescope, and the attenuation correction factor and its estimated uncertainty are listed together with the statistical standard deviations for each value of the cross section.

Lab angle	C.m. angle	Attenuation correction factor	$d\sigma/d\Omega$ (lab) (mb/sterad)	$d\sigma/d\omega$ (c.m.) (mb/sterad)	Statistical uncertainty (%)	Estimated uncertainty in attenuation correction (%)
	Incident proton energy about 93 Mev at center of target					
5°	6° 22′	1.213	225	140	4.2	5.8
6°	7° 36′	1.213	133	82.3	2.4	5.8
7°	8° 57′	1.213	103	64.3	3.2	5.8
8°	10° 12′	1.212	116	72.0	1.6	5.8
9°	11° 28′	1.212	124	77.0	4.5	5.8
10°	12° 44′	1.212	131	81.7	1.4	5.8
12°	15° 22′	1.211	128	79.9	1.4	5.7
15°	19° 2′	1.209	105.5	66.3	0.8	5.6
22½°	28° 26′	1.203	55.4	35.6	1.4	5.5
30°	37° 46′	1.195	22.1	14.6	1.4	5.4
37½°	46° 58′	1.187	8.2	14.1	2.6	5.2
45°	56° 6′	1.176	3.34	5.58	2.7	4.8
50°	61° 54′	1.167	2.46	2.38	3.6	4.6
60°	73° 28′	1.149	1.46	1.16	4.7	4.4
75°	89° 58′	1.122	0.50	0.46	6	3.9
82½°	97° 50′	1.110	0.28	0.27	16	3.4
90°	105° 26′	1.096	0.11	0.11	18	3.2
	Incident proton energy about 98 Mev at center of target					
60°	73° 28′	1.149	1.41	1.13	5	4.4
90°	105° 26′	1.096	0.073	0.076	21	3.2
105°	119° 51′	1.084	0.036	0.043	18	2.7
120°	133° 14′	1.066	0.0035	0.005	120	2.1
135°	145° 46′	1.054	0.024	0.037	32	1.8
150°	157° 34′	1.045	0.075	0.128	24	1.5
165°	168° 54′	1.040	0.124	0.224	12	1.3
170°	172° 38′	1.039	0.155	0.283	7	1.3

[10] The attenuation correction factors for protons and deuterons in this telescope have been determined by calculation and checked experimentally: see J. M. Teem, Ph.D. thesis, Harvard University, 1954 (to be published). The magnitude of these corrections varied from 4% to 21% for the proton spectra, and from 4½% to 11% for the $He^4(p,d)He^3$ deuterons.

[11] B. Cork, Phys. Rev. **89**, 79 (1953).

[12] A. F. Wickersham, Phys. Rev. **107**, 1050 (1957).

[13] M. K. Brussel and J. H. Williams, Phys. Rev. **106**, 286 (1957).

[14] J. Benveniste and B. Cork, Phys. Rev. **89**, 422 (1953).

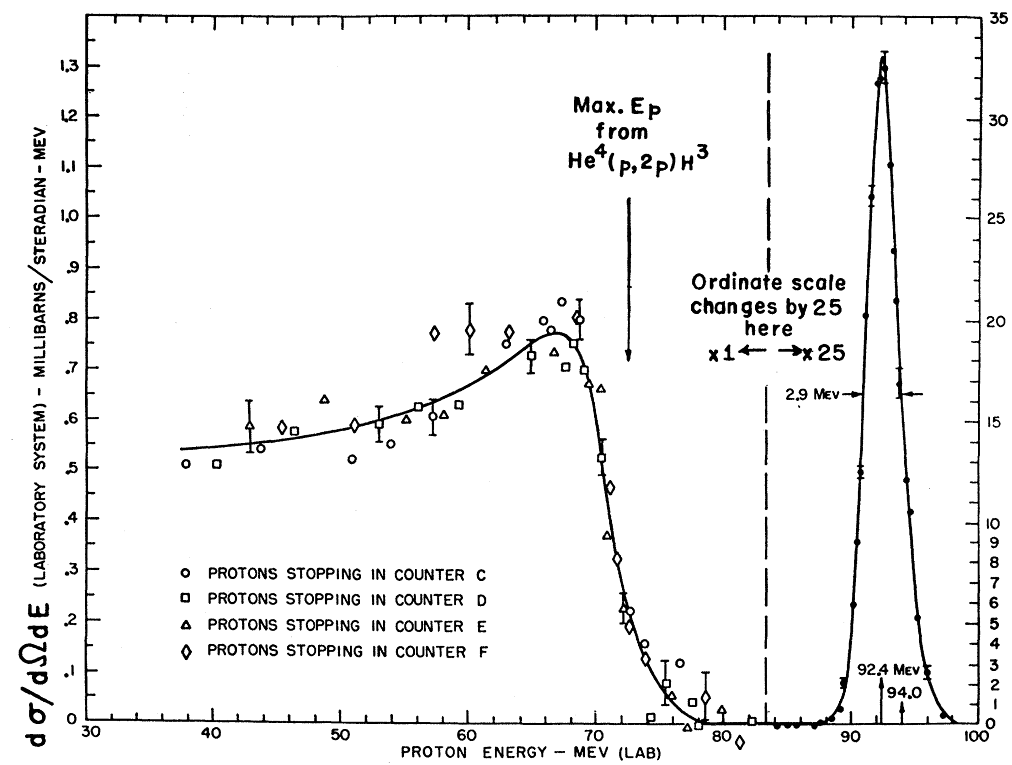

FIG. 3. 94-Mev (p+He^4) scattering: Proton energy spectrum at $\theta_{lab}=15°$.

the proper stopping interval to an adjacent one. There is some indication in the data that counter F may at times have been counting systematically by as much as 10% too high a rate.

III. DISCUSSION

Several qualitative features of the elastic scattering are readily apparent from Fig. 4. The cross-section dependence upon angle is roughly exponential, falling with an exponential coefficient of approximately 3.8 rad^{-1} to a value roughly 10^{-4} of the forward scattering cross section at 135°, and then rises again to a backward peak of the order of 5×10^{-3} of the forward cross section. Superimposed upon this general trend are two minima, one at 9° which is due to the nuclear-Coulomb interference, and one broad shallow dip at about 57° which is probably due to diffraction. The backward peaking can be understood qualitatively as due to an exchange or "pickup" process, in which the incident proton exchanges with a proton in the He^4 nucleus, and is analogous with the backward peak in proton-deuteron scattering.[5,10] In the spirit of the "transparent nucleus" Born approximation discussed above, one could expect the cross section in this region to be primarily determined by a "pickup" amplitude proportional to the square of the "single nucleon" momentum wave function of an alpha particle (i.e., of a proton-triton configuration).

There are also several qualitative features that are worth noting in the three inelastic spectra of Figs. 3, 6 and 7. Since there are certainly no bound excited states of He^4, the maximum energy that an incident 94-Mev proton scattered inelastically can possess can be calculated from the kinematics of reaction 3, Table I, assuming that an unbound proton and triton recoil together with zero relative velocity. The upper energy limits of the spectra are seen to agree with these limits

TABLE III. Angular distribution of deuterons from $He^4(p,d)He^3$ for 93-Mev protons. Background (generally less than 2%) has been subtracted. The data have been corrected for absorption and scattering in the range telescope, and the attenuation correction factor and its estimated uncertainty are listed together with the statistical standard deviations for each value of the cross section.

Θ Lab angle	θ C.m. angle	Attenuation correction factor	$d\sigma/d\Omega$ (lab) (mb/sterad)	$d\sigma/d\omega$ (c.m.) (mb/sterad)	Statistical uncertainty (%)	Estimated uncertainty in attenuation correction (%)
6°	8° 55′	1.110	34.5	16.0	1.5	3.0
8°	11° 53′	1.109	23.0	10.7	1.4	2.9
10°	14° 50′	1.108	17.3	8.07	2.3	2.8
12°	17° 48′	1.107	10.8	5.10	2.1	2.7
15°	22° 13′	1.105	6.15	2.92	2.1	2.6
17½°	25° 54′	1.103	4.67	2.24	2.6	2.5
20°	29° 33′	1.101	3.74	1.81	2.4	2.4
22½°	33° 12′	1.098	4.70	2.30	2.8	2.3
26°	38° 17′	1.094	4.49	2.24	2.3	2.3
27½°	40° 26′	1.092	4.20	2.11	2.5	2.2
30°	44° 2′	1.088	3.98	2.03	2.3	2.1
33°	48° 18′	1.083	3.24	1.69	2.5	2.0
37½°	54° 39′	1.081	2.06	1.11	2.9	2.0
41°	59° 30′	1.068	1.48	0.82	4.3	1.5
45°	65° 0′	1.059	0.73	0.42	5.0	1.3
50°	71° 43′	1.045	0.59	0.36	4.0	1.0

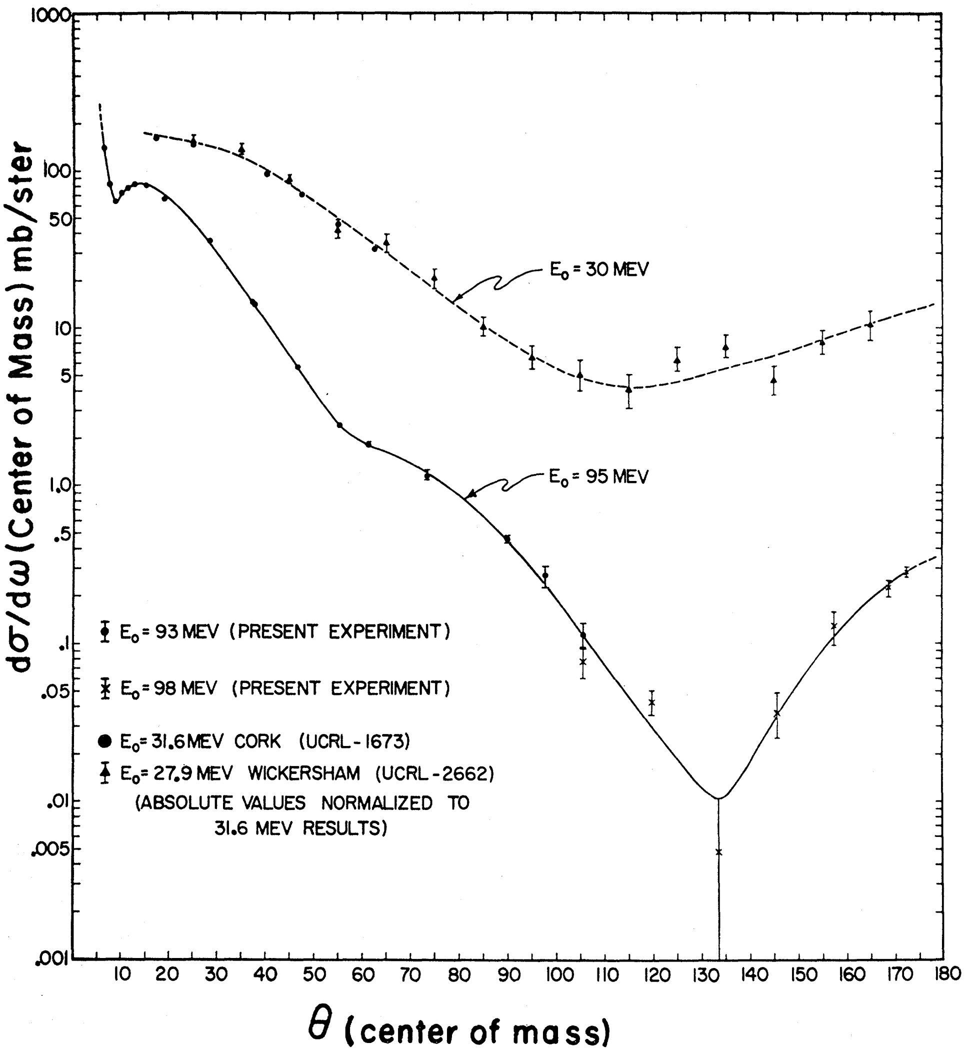

FIG. 4. Elastic proton-helium differential cross section.

within the energy resolution of the experiment. Similar upper energy limits can be calculated for the other reactions of Table I. To a good approximation they will fall lower than the indicated limit by just the difference in Q values of the reactions.

Each of the three inelastic proton spectra is characterized by a broad peaking (roughly 10 Mev wide) of the cross section about an energy roughly 6 Mev below the upper kinematic limit. The cross sections for the lower energy protons (corresponding to an excitation of the He^4 nucleus roughly 5 Mev to 20 Mev in excess of the energy of complete dissociation) approach a constant value of 0.55 mb/sterad-Mev, independent of either laboratory angle or proton energy. This behavior is in pointed contrast to the inelastic proton spectra obtained at the same incident energy for a wide range of elements from Li to Bi.[15] While numerous inelastic peaks, corresponding to nuclear excitation of discrete levels or several unresolved levels, are observed among the light nuclei, they are superimposed on an inelastic continuum with an energy dependence that has been fitted by the relationship $KE\exp(-E/k)$, where E is the inelastic proton energy in the center-of-mass system, and K and k are empirical constants. The falling off of the inelastic continua with increasing energy, which is apparently most emphasized in the lightest nuclei, is obviously not demonstrated for He^4, where the cross section appears constant or increases with increasing energy. One should not necessarily expect that the energy dependence of the inelastic proton continuum from He^4 should be predicted by any model that works for nuclei even as light as Li^7 and Be^9. Nevertheless, simple phase-space arguments would indicate that, near the upper end of the spectrum, one might indeed expect a decreasing cross section with increasing inelastic proton energy, since there is more phase space available for large momentum transfers than for small. The

[15] K. Strauch and F. Titus, Phys. Rev. 104, 191 (1956).

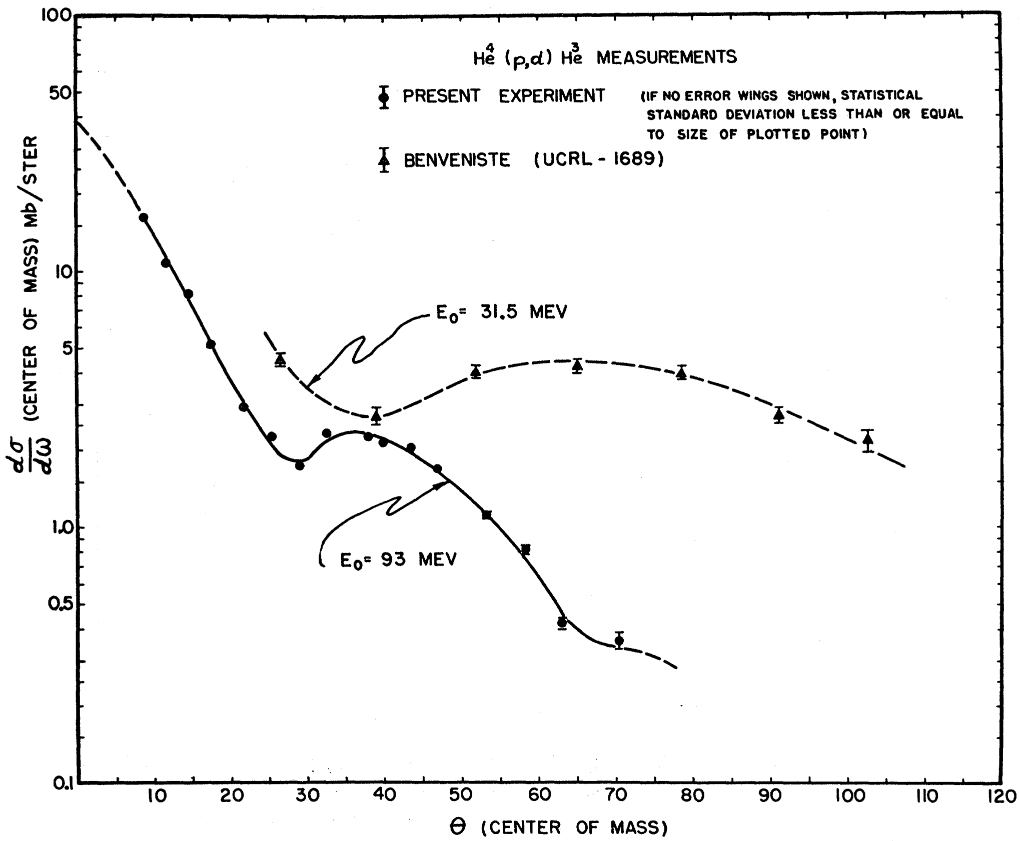

FIG. 5. $He^4(p,d)$-He^3 differential cross section (deuteron "pickup" scattering).

observed inelastic spectra from He^4 would indicate a preference for energy transfers of the order of 26 Mev, possibly suggesting strong interaction between parts of the dissociated He^4 nucleus in virtual or continuum states. Before discussing this interpretation, however, we should first consider another mechanism which could produce peaks in the inelastic continuum.

One might hope that at sufficiently high interaction energy the spectra of protons from reactions (3) and (4), Table I, could be deduced qualitatively, at least, by assuming that the incident proton is quasi-elastically scattered from a single nucleon in the He^4 nucleus.[16] (Such a picture is certainly consistent with the "transparent nucleus" Born or impulse approximations that we were trying to apply to this work.) This quasi-elastic scattering will differ kinematically from scattering from the free nucleon in that here part of the kinetic energy of the incident nucleon is used to liberate the bound target nucleon, and also because the struck nucleon is in motion in the laboratory system, due to the nucleon's internal momentum distribution in the nucleus. Thus the spectrum predicted by this model will consist of a broad peak, modified at the upper energy end by the inelastic kinematical limit and centered around an energy which is different from the "free nucleon" value at that angle (approximately $E_0 \cos^2\theta_{\text{lab}}$) due to the effect of the binding energy of the struck nucleon.

It would be of interest to investigate the applicability of the quasi-elastic scattering interpretation to the present results. Unfortunately, it is not a simple matter to calculate the theoretically expected inelastic spectrum resulting from quasi-elastic scattering, nor even to estimate the energy of the peak that should result from this process. The difficulty lies in the fact that although the total energy of the two nucleons leaving the nucleus is reduced, from the energy of the incident nucleon, by the binding energy of the ejected nucleon, this reduction in energy cannot be associated in a simple way with one or the other of the two departing nucleons. A crude semiclassical approach suggests that when one of the nucleons leaving is a relatively high-energy proton, then it will not show much of the binding-energy effect, which will then be exhibited by the other, lower energy nucleon leaving the He^4 nucleus. This conclusion is reached in the following way. If a proton leaves the (He^4+p) system with a majority of the energy of the incident proton, then it leaves at a time when the remaining nucleons consist of the same set found in He^4;

[16] This model has been successful in explaining the qualitative features of the inelastic scattering continua produced by 340-Mev and 270-Mev incident nucleons and has been used to infer nucleon momentum distributions in nuclei from such data. See, for example: Cladis, Hess, and Moyer, Phys. Rev. **87**, 425 (1952); and J. M. Wilcox and B. J. Moyer, Phys. Rev. **99**, 875 (1955).

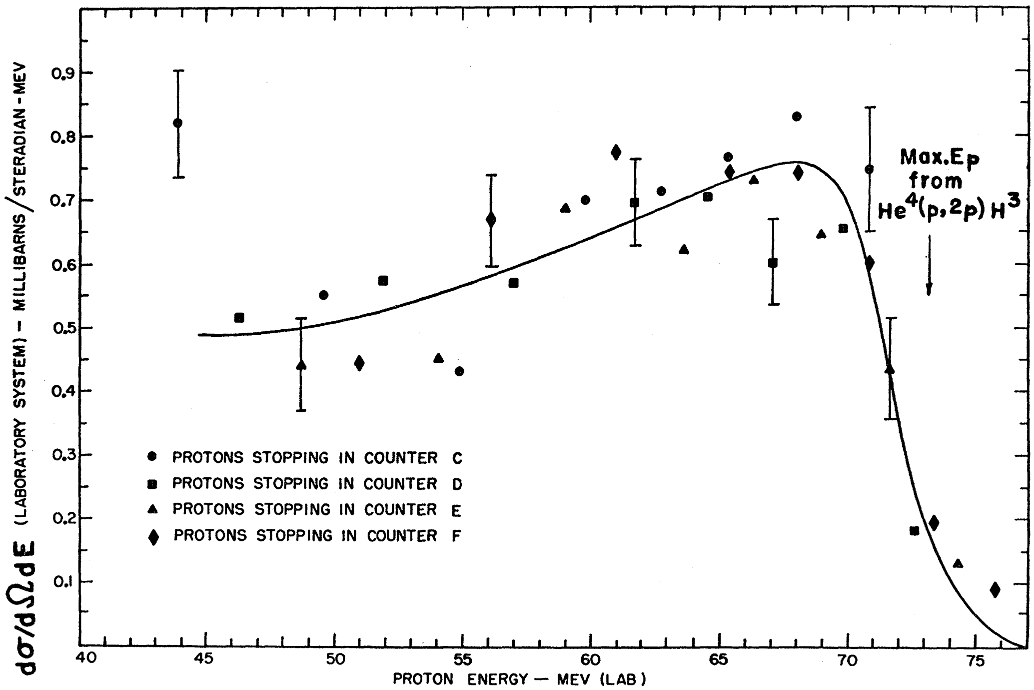

FIG. 6. 94-Mev (p+He^4) scattering: Inelastic proton-energy spectrum at $\theta_{lab}=10°$.

this set does not interact very strongly with an additional proton, and hence the departing nucleon will not be slowed appreciably. This is obviously a very crude picture. When numerical estimates are made on this model, it can only be said that the peaks seen in the inelastic spectra reported here are not inconsistent with a quasi-elastic scattering mechanism.

A new measurement of the $He^4(p,p')$ spectrum for 181-Mev incident protons has recently been reported.[17] That work shows broad peaks similar to those found

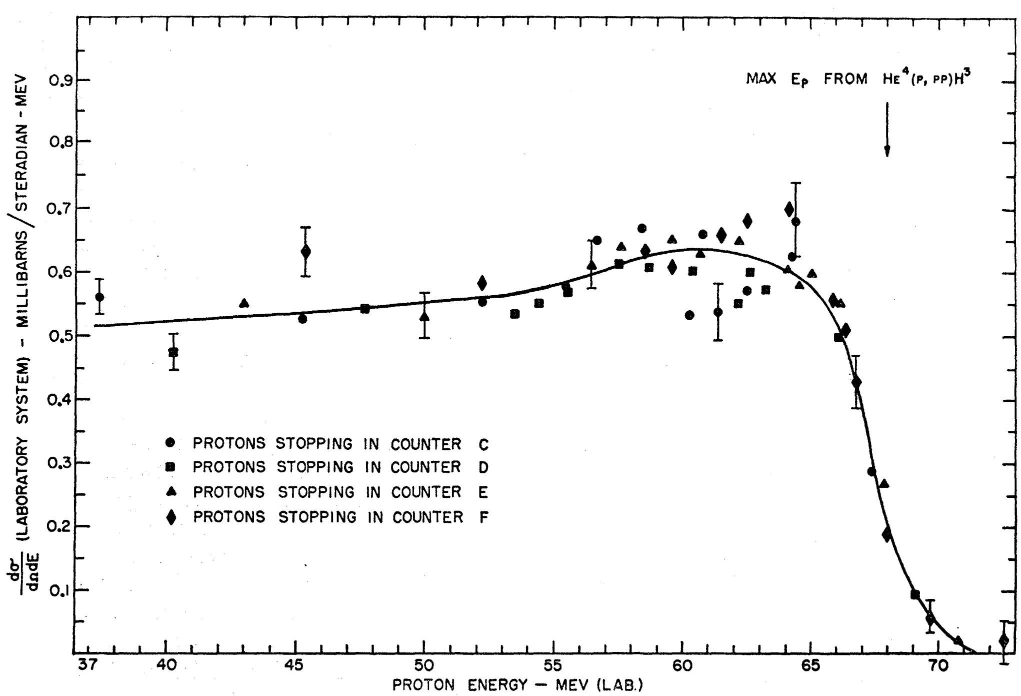

FIG. 7. 94-Mev (p+He^4) scattering: Inelastic proton-energy spectrum at $\theta_{lab}=30°$.

[17] Tyren, Tibell, and Maris, Nuclear Phys. 4, 277 (1957).

here, although somewhat more distinct. The greater distinctness can be interpreted as resulting from the greater transparency of the He^4 nucleus at the higher energy; the position of the peak, at the various angles measured, is again consistent with the quasi-elastic interpretation.

The history of past investigations, experimental and theoretical, concerned with possible excited states of the He^4 nucleus is reviewed thoroughly in references 6 and 14. The results of the present experiment are in complete agreement with those at lower energies in showing no evidence of bound excited states. There is also agreement on the absence of any evidence for inelastic groups corresponding to isolated virtual states with widths less than 3 Mev. With regard to the possible existence of virtual states, the present data could be qualitatively interpreted as resulting from a broad virtual level or group of levels, $\gamma \sim 10$ Mev, $E \sim 25$ Mev above the ground state; although, as discussed above, these data may be explainable as due to quasi-elastic scattering. Both of these interpretations are consistent with the other reported proton-He^4 measurements. No peaks have previously been observed in the measurements at lower incident energies, but this may be understood as due to the fact that the lower energies did not permit exploration of the detailed energy spectrum over a very broad energy range. The recent measurement[17] at 181 Mev is also consistent with both the quasi-elastic and the virtual-level interpretations.

It would appear that a fruitful study might be made of p-He^4 inelastic scattering in a helium bubble chamber or cloud chamber, since in this case the inelastic spectra for each of the reactions in Table I could be measured separately to determine whether there is, indeed, a strong attractive interaction between some of the nuclear groups that result from the particle dissociation. This should show up in an angular correlation of the products and in a kinematic behavior for the inelastically scattered proton similar to that appropriate to two-body reactions.

Recent measurements of the inelastic scattering of 400-Mev electrons from He^4 at 60° have also shown some indication of a similar broad peak[7] in the spectrum. In this experiment, this peak shows up as a bump, possibly only just apparent within the counting statistics, on a broad continuum. The width of this peak is also of the order of 10 Mev, but the estimated energy is only 21 Mev below the elastically scattered electrons. Within the accuracies of the two experiments, this difference is probably not significant. It would be interesting to compare the present results with higher accuracy measurements of the inelastic proton-He^4 scattering at several angles.

The $He^4(p,d)He^3$ differential cross section (Fig. 5) shows a definite minimum at about 28° and a suggestion of a second minimum at about 67°. Qualitatively, this behavior is quite similar to the results at 32 Mev. We

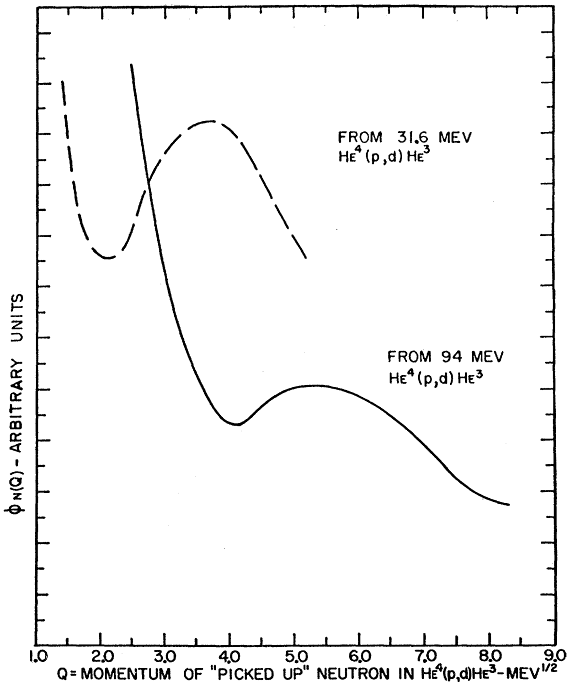

FIG. 8. Neutron momentum wave function amplitude for a neutron "picked up" from a He^3+n configuration in He^4 as deduced from a Chew-Goldberger type analysis of $He^4(p,d)He^3$ results.

have made a Chew-Goldberger type Born approximation analysis[2,3] of our 94-Mev data to infer the momentum density function for a neutron in a (n-He^3) configuration in the He^4 nucleus. The results of this analysis are shown in Fig. 8 in which is plotted the momentum wave function amplitude (the square root of the momentum density). Unfortunately, analysis of the 32-Mev data gives a momentum density function (also shown in Fig. 8) which is completely incompatible with that inferred from the higher energy data. This is in sharp distinction to the consistency of the momentum distributions inferred for the loosely-bound neutron in Be^9 for (p,d) measurements from 16 Mev to 95 Mev.[4] This failure indicates that He^4 is probably too compact a structure to be well treated by this type of "single-particle, transparent-nucleus" Born approximation approach, at least at energies up to 32 Mev. Such an approach may nevertheless be correct at 95 Mev. In fact, from the interpretation of (p,d) measurements on several nuclei at 95 Mev, there is reason to believe that there is indeed some accuracy in this approximation for He^4 at this higher energy. (See Fig. 11 and the associated discussion, in reference 3, for further details.)

At lower energies the "opaque-nucleus" Born approximation has been employed by a number of workers[18–20]

[18] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951) and Phys. Rev. **106**, 272 (1956).

[19] W. Tobocman, Phys. Rev. **94**, 1655 (1954) and W. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955).

[20] Austern, Butler, and McManus, Phys. Rev. **92**, 350 (1953).

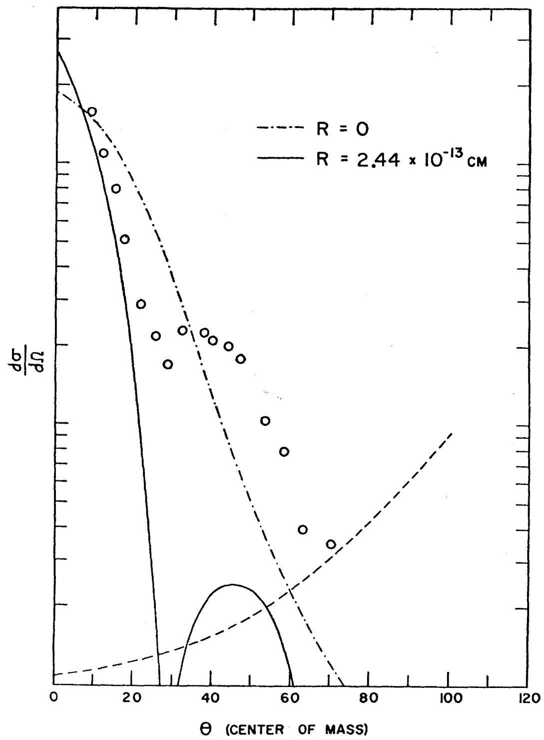

FIG. 9. $He^4(p,d)He^3$: $E_p=94$ Mev; Tobocman's fit of data.

with considerable success in interpreting data from low-energy (p,d) and (d,p) reactions. The 32-Mev He^4-$(p,d)He^3$ has been analyzed in this manner both by Benveniste and Cork[14] and by Tobocman.[21] The parameter adjusted in this model to fit the data is the effective radius of the He^3 nucleus, which determines the positions of the cross-section minima. The qualitative features of the 32-Mev data are reasonably well represented by this model (see, for example, Fig. 6 of reference 14), except that the theoretical cross section falls below the experimental values at larger angles. It is also interesting to see how well this approximation can account for the $He^4(p,d)He^3$ data at 94 Mev. The results of Tobocman's analysis[21] are shown in Fig. 9.

The qualitative features of the data would seem to be almost as well represented by this model at 95 Mev as they are at 32 Mev, except for an even greater disparity in magnitude at larger angles. However, there is a significant difference in the values that must be assigned the He^3 radius, R, at the two energies. Benveniste and Cork[14] used a value of $R=4.2$ fermis (one fermi$=10^{-13}$ cm) and Tobocman[21] achieved a reasonable fit to the 32-Mev data with $R=5.5$ fermis. The value that Tobocman has found to provide the proper angles for the minima at 95 Mev is $R=2.44$ fermis. The dashed curve that rises for increasing angle in Fig. 9 was calculated from the "exchange" amplitude associated with the pickup of a deuteron by the proton to form He^3. It is apparent that this process may become important at the larger angles. The curve calculated for $R=0$ is also shown and is seen to give much closer agreement in magnitude with the experimental points, which probably indicates that the "transparent-nucleus" approximation might, indeed, be a better approximation at this energy. While the "opaque-nucleus" picture is of questionable validity at this energy, nevertheless the analysis suggests that both the observed minimum at 29° and the probable second minimum at 67° possibly arise from diffraction effects.

Because of the uncertainties involved in the assumptions, as emphasized by the inconsistencies that arise in the analysis of the $He^4(p,d)He^3$ results at the two energies, we have not attempted to carry the program of analysis outlined in Sec. I any further. It would be worthwhile, we believe, to look at this problem again whenever similar data are available on the p-He^4 interaction at energies somewhat below and above that used here, to see if a consistent program of analysis can then be carried out.

ACKNOWLEDGMENTS

We are especially indebted to Dr. U. E. Kruse, who engaged in the initial planning and setting up of this experiment. We also wish to thank the many members of the Cyclotron Laboratory staff who helped make these measurements possible. Much assistance in taking the data and making calculations was given by P. F. Cooper, R. Chrenko, R. Fullwood, A. Erwin, and R. Verdier.

It is a pleasure to thank Dr. Fay Selove for helpful discussion on the available information as to the possible existence of excited states of He^4.

[21] W. Tobocman (private communication). We are grateful to Dr. Tobocman for helpful discussions of this problem and for his permission to show his unpublished results in Fig. 9.