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Scattering of 40-Mev Protons from He^4†

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The existence of an excited state in He^4 may be investigated by bombarding these nuclei with a monoenergetic beam of protons and looking for a group of inelastically scattered protons corresponding to excitation of the state. Using this technique at a bombarding energy of 32-Mev, Benveniste and Cork found no evidence of a state in He^4 of excitation energy less than 23 Mev. The 40-Mev beam of the Minnesota proton linear accelerator has been used to extend the search for a state in He^4 to higher excitation energies. A gas target was bombarded and particles emitted at forward angles were detected in a scintillation counter which measured their energy. By observing the energy loss in traversing thin foils, the masses of the emitted particles were determined. Elastically scattered protons and recoil He^4 were seen, as well as deuterons and recoil He^3 from the ground state (p,d) reaction. A continuum of protons from $(p,2p)$ and (p,pn) reactions was observed. No evidence was found for a group of inelastically scattered protons corresponding to excitation of a state in He^4 of energy less than 28 Mev.

INTRODUCTION

THE purpose of this experiment is to investigate the existence of an excited state in He^4. In this section a short review of the present status of this subject will be presented.

In 1936, theoretical arguments were given which set an upper limit on the excitation energy of the first few excited states of He^4.[1,2] These arguments were based on sum rules and required a knowledge of the ground-state wave function. According to the best estimates of the ground-state wave function which could be made at the time, the upper limits of the excitation energies indicated the existence of two bound (excitation$<$20 Mev) excited states.

Little experimental evidence was available on this subject prior to the investigation, commencing in 1950, of the reaction $H^3(p,\gamma)He^4$. In the first experiment on this reaction, the excitation function was found to increase rapidly up to the maximum available energy of 2.5 Mev.[3] These data were fitted by assuming a single virtual state in He^4 at an excitation energy of 21.6 Mev, and with a half-width of 1 Mev. Furthermore, the experiment indicated the presence of only a single 21.6-Mev γ ray, which argues against the existence of a bound state in He^4. Later, calculation of the nonresonant capture of p-wave protons by H^3 showed that the results of this experiment could be explained without assuming a state in He^4.[4] Extension of the $H^3(p,\gamma)He^4$ experiment to higher bombarding energies demonstrated that the excitation function continues to increase, showing no resonant structure to a maximum energy of 7.3 Mev.[5–7] The results of these experiments are also in qualitative agreement with the calculation based on nonresonant capture. However, isotopic spin selection rules may prohibit radiative transitions from the first excited state to the ground state in He^4.[8] Thus, to the extent that these selection rules apply, the $H^3(p,\gamma)He^4$ reaction could not show a resonance due to the first excited state in He^4.

Some information exists concerning other reactions in which, as in the case of $H^3(p,\gamma)He^4$, the intermediate system is He^4. Examples are: $H^3(p,p)H^3$,[9] $H^3(p,n)He^3$.[10] Excitation functions have been measured up to several Mev with no conclusive evidence for an excited state in He^4 being found.

Information concerning an excited state in He^4 may also be obtained by investigating inelastic scattering reactions such as $He^4(p,p')He^4$. In these experiments, He^4 is bombarded with monoenergetic protons and a search is made for a group of inelastically scattered protons corresponding to excitation of the state. These experiments have the advantage, compared to the experiments described in the previous paragraphs, that it is no more difficult to search for bound states than to search for virtual states.

Using the inelastic proton scattering technique at a bombarding energy of 32 Mev, Benveniste and Cork found no evidence of a state in He^4 of excitation energy less than 23 Mev.[11] These results were confirmed by Wickersham.[12] Since a state lying just above the energy range investigated by these experiments would be

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virtual by only about 3 Mev, it is possible that a state could exist, at excitation energies higher than those investigated, with a width not too large to preclude observation. Consequently, it is worthwhile extending the search for a state in He^4 to higher excitation energies.

In the experiment reported here, this has been accomplished by using bombarding protons of higher energy. In this experiment, a gas target of He^4 is bombarded by the 40-Mev beam of the Minnesota proton linear accelerator. Particles emitted at forward angles are detected in a scintillation counter which measures their energy. By observing the energy loss in traversing thin foils, the masses of the emitted particles are determined. A search is made for a group of inelastically scattered protons corresponding to excitation of a state in He^4. With this technique, it is possible to investigate the existence of a state in He^4 of excitation less than 28 Mev. Thus the range investigated is extended to include states which are virtual by less than 8 Mev.

EXPERIMENTAL PROCEDURE AND RESULTS

The 40-Mev beam from the Minnesota proton linear accelerator is deflected into the experimental area by a magnet located between the second and third sections of the machine. Before entering the magnet, the beam passes through a thin Al stripping foil to eliminate the presence of H_2^+ ions in the deflected beam. The deflected beam then passes through a system of collimating diaphragms and through a thin Al entrance window into the scattering chamber.

The scattering chamber is filled to $\frac{1}{2}$ atmosphere with He^4 which is purified by passing it through an activated-charcoal trap maintained at liquid nitrogen temperature. The trap removes all impurities except Ne and H_2. If either of these impurities were present in a significant amount they would manifest themselves by elastically scattering protons which could be resolved from the protons elastically scattered from He^4. From the energy distribution of scattered protons, it can be shown that the amount of Ne and H_2 present is negligible.

Particles which scatter at an angle of 30°, from a region in the center of the chamber, pass through a second system of diaphragms and through a thin Al exit foil and then enter a shielded NaI scintillation counter. The beam continues through the scattering chamber and is collected in a Faraday cup and integrated by a feedback electrometer circuit.

Pulses from the scintillation counter are sent through a preamplifier and amplifier and into a ten channel pulse-height analyzer. The energy sensitivity of the detection system is calibrated from the observed pulse height of elastically scattered protons, which have an energy of 37.2 Mev upon entering the NaI crystal.

The relation between the observed number of counts per unit integrated beam and the cross section was obtained from a measurement of p-p scattering made under the same conditions of geometry, gas pressure, etc., used in the He^4 scattering experiment. The cross-section conversion factor obtained in this manner is known with essentially the same accuracy as the p-p scattering cross section. This procedure eliminates the necessity of performing a tedious solid angle calculation.

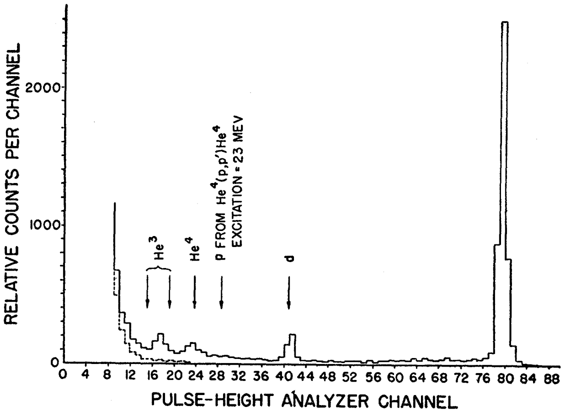

FIG. 1. Pulse-height distribution of particles emitted at 30° from He^4 bombarded with 40-Mev protons.

Figure 1 shows a pulse-height distribution of particles emitted at 30° from He^4 bombarded with 40-Mev protons. The peak near channel 80 is the elastically scattered protons. The arrow labeled d shows the calculated location of deuterons from the reaction $He^4(p,d)He^3$ leading to the ground state of He^3. The arrow labeled "He^4" shows the calculated location of recoil He^4 from the elastic scattering process. Correction has been made for the nonlinear response of NaI to He^4.[13] The two arrows enclosed by the bracket labeled "He^3" show the approximate range of calculated locations corresponding to recoil He^3 from the ground state $He^4(p,d)He^3$ reaction. The calculated location is uncertain because the response of NaI to He^3 has not been measured (to the knowledge of the author). The continuum of pulses, in the region between the peak near channel 80 and the peak near channel 40, consists of: (i) elastically scattered protons whose energies have been degraded by slit scattering, (ii) elastically scattered protons which have suffered a nuclear interaction in the NaI crystal before they have traversed their range. Measurements of the specific ionization of the particles comprising the various peaks, indicate that the continuum to the left of the peak near channel 40 also consists of protons. In this region, the continuum is the sum of the two effects just mentioned plus a real low-energy proton continuum from $He^4(p,2p)H^3$ and $He^4(p,pn)He^3$ reactions. The Q of these reactions is such that the low-energy proton continuum will begin just to the left of the peak near channel 40. To the left of channel 14 the number of counts per channel increases rapidly. This is due to a background of uncharged

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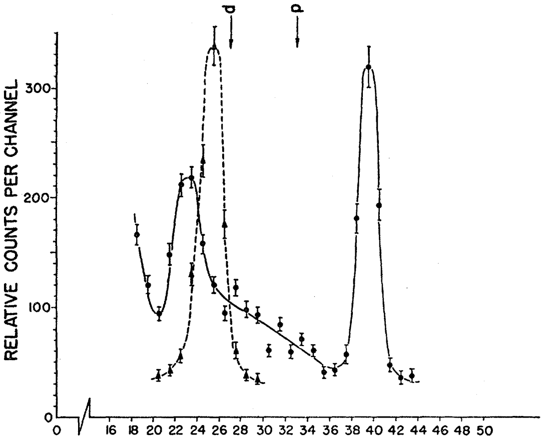

FIG. 2. Identification of deuteron group.

radiation from diaphragms, Faraday cup, etc. The background is measured by placing an absorber in front of the scintillation counter thick enough to stop the longest range particle present. It is also measured by observing the counting rate when the scattering chamber is evacuated. The dotted line shows the measured pulse-height distribution of the background.

The arrow labeled "*p* from $\mathrm{He}^4(p,p')\mathrm{He}^4$" shows the calculated location of protons inelastically scattered from a state in He^4 of 23-Mev excitation. Protons inelastically scattered from a state of lower excitation energy would be found at greater pulse height, and vice versa. If the peak near channel 40 is due to deuterons, then the absence of a group of inelastically scattered protons confirms the prior evidence[11,12] that there is no state in He^4, of excitation energy less than 23 Mev, which can be observed by inelastic proton scattering.

The agreement between the calculated and observed positions of the three low pulse-height peaks implies that they consist of deuterons, He^4, and He^3, respectively. However, it is necessary to make a positive identification. It is also necessary to investigate the shape of the continuum under the He^4 and He^3 peaks. Both of these ends are accomplished by utilizing the dependence of the specific ionization of a particle on its mass and charge.

In Fig. 2, the data connected by the solid line show the groups tentatively identified as deuterons (channel 40) and as He^4 (channel 23). The data connected by the dashed line are obtained under identical conditions except that a 0.020-in. Al absorber is placed so that the emitted particles traverse the absorber before entering the scintillation counter. In both cases, the background has been subtracted. The arrow labeled *p* shows the calculated location, with the absorber in place, of the peak that was at channel 40, assuming the peak to consist of protons. The arrow labeled *d* shows the calculated location, assuming the peak to consist of deuterons. If the peak consisted of He^4, then the He^4 would be completely stopped by this absorber. The discrepancy between the location of the peak with the absorber in place and the location of the arrow labeled *d* is roughly equal to the sum of the errors involved in making the measurement and calculation. Thus, the identity of the deuteron peak is established.

In Fig. 3, the data connected by the solid line show the groups tentatively identified as He^4 (channel 23) and He^3 (channel 17). The data connected by the dashed line show the effect of inserting a 0.002-in. Al absorber. Background has been subtracted. The arrows labeled *p*, *d*, and He^4 show the calculated locations of the peak originally at channel 23, with absorber in place, assuming it to consist of: protons, deuterons, and He^4. It is apparent that the peak originally at channel 23 consists of He^4. The peak at channel 17 has been shifted into the region where excessive background prevents obtaining data.

In Fig. 4, the data connected by the solid line show the He^4 group (channel 23) and the group tentatively identified as He^3 (channel 17), while the data connected by the dashed line shows the effect of inserting a 0.0005-in. Al absorber. Background has been subtracted. The equality of the displacement of the two peaks indicates that the specific ionization of the group originally at channel 17 is equal to the specific ionization of the He^4 group. This is in agreement with the assumption that the peak originally at channel 17 consists of He^3. (Specific ionization is approximately proportional to the quantity Z^2M/E, which has about the same value for both groups.)

The final phase of the experiment consists of investigating the continuum of protons from $(p,2p)$ and (p,pn) reactions lying to the left of the deuteron group—particularly the region underneath the He^4 and He^3 groups (see Fig. 1). This is accomplished by inserting a 0.003-in. Al absorber in front of the scintillation counter. The effect of this absorber is to displace both the He^4 and He^3 groups into the region where back-

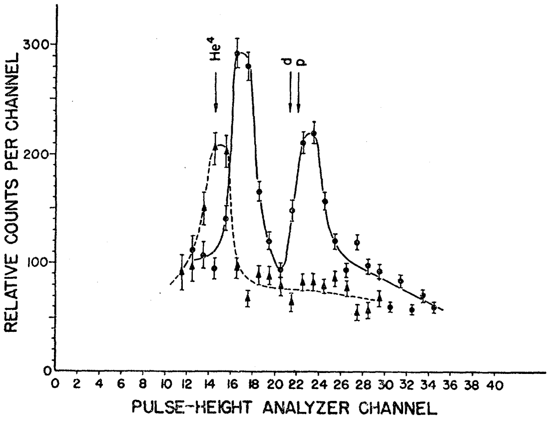

FIG. 3. Identification of He^4 group.

ground is so large that data cannot be obtained. However, since the specific ionization of protons or deuterons is much smaller than the specific ionization of He^4 or He^3, the absorber has little effect on the other features of the pulse height distribution. The data obtained under these conditions are shown in Fig. 5. Background has been subtracted. The group at channel 40 consists of deuterons from the (p,d) reaction. The arrows show the locations at which groups of inelastically scattered protons would be found, corresponding to excitation of states in He^4 of energy 23 Mev and 28 Mev. Previous experiments have shown that there is no evidence for a state of excitation energy less than 23 Mev.[11,12]

The significant results of the present experiment are contained in the data lying to the left of the arrow labeled 23 Mev. It is apparent that these data show no evidence for a group of inelastically scattered protons. The data are consistent with the assumption that the shape of the continuum is given by the straight line drawn in the figure. It is possible to estimate an upper limit to the cross section for observing a group of inelastically scattered protons in this range, if some assumption is made concerning the width of the group. The 0.9-Mev full width of the deuteron group in channel 40 is entirely due to experimental resolution. If state existed in He^4, in the range 23 Mev to 28 Mev and with a width less than about 0.5 Mev, it would lead to a group of inelastically scattered protons in the region under consideration and of width equal to the experimental resolution. Such a group would be observed unless the cross section were less than about 1.0 millibarn per steradian in the laboratory system. Therefore, under this assumption,

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{He}^4(p,\,p')\mathrm{He}^4} \leqslant 1.0\,\frac{\text{millibarn}}{\text{steradian}} \quad (30^\circ \text{ in lab system}).$$

Larger values for upper limits to the cross section would apply to inelastic scattering from broader states. The upper limit to the cross section, transformed to the center-of-mass system in the case of 28 Mev excitation energy, is

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{He}^4(p,\,p')\mathrm{He}^4} \leqslant 0.25\,\frac{\text{millibarn}}{\text{steradian}} \quad (65^\circ \text{ in c.m. system}).$$

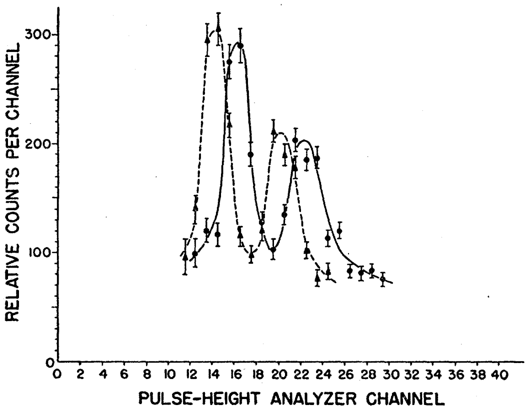

FIG. 4. Identification of He^3 group.

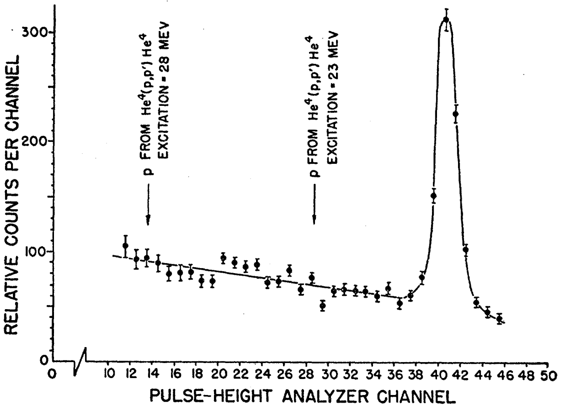

FIG. 5. Proton continuum as observed with 0.003-in. Al absorber in place.

Additional data were obtained at a laboratory scattering angle of 60°. At this angle, it was only possible to investigate the existence of states in He^4 of excitation energy less than 25 Mev. Again no evidence for a state was found.

The cross section in the laboratory system for the elastic scattering of 40-Mev protons from He^4 is

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{He}^4(p,\,p)\mathrm{He}^4} = 110\pm10\,\frac{\text{millibarns}}{\text{steradian}} \quad (30^\circ \text{ in lab system}).$$

The cross section for the ground state (p,d) reaction is

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{He}^4(p,\,d)\mathrm{He}^3} = 10\pm1\,\frac{\text{millibarns}}{\text{steradian}} \quad (30^\circ \text{ in lab system}).$$

CONCLUSION

Previous inelastic scattering experiments investigated He^4 for states of excitation energy less than 23 Mev.[11,12] This includes all bound states as well as states which are virtual by less than 3 Mev. No evidence for a state was found. The present experiment extends the range investigated to 28-Mev excitation energy, which includes all bound states and states virtual by less than 8 Mev. Again, no evidence for a bound state is found. If a virtual state exists in this energy range, of full width less than 0.5 Mev, then the cross section for exciting it by inelastic scattering of 40-Mev protons is less than about 0.25 millibarn per steradian at 65° in the center-of-mass system. Larger values for upper limits to the cross section would apply to inelastic scattering from broader states.

The search for a state in He^4 can be carried to still higher excitation energies by using more energetic bombarding particles. However, since it is apparently a general rule that the width of a virtual state increases with increasing excitation energy, and since broad states are difficult to detect, it does not seem very probable that a state will be found at higher excitation energy.

The predicted existence[1,2] of two states in He^4 has not been confirmed by experiment. The calculations leading to this prediction were performed in 1936. It would be interesting to repeat these calculations using more recent estimates of the ground-state wave function.

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Nuclear Moments of Am^{241} and Am^{243}[†]

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The following values have been derived from measurements of hyperfine structure in the spectrum of americium: $\mu_{241}=+1.4$ nm, $Q_{241}=+4.9\times10^{-24}$ cm^2, $\mu_{241}/\mu_{243}=+1.00\pm0.01$, $Q_{241}/Q_{243}=+1.00\pm0.01$.

HYPERFINE structure in the americium spectrum has been measured in high orders of a 30-foot spectrograph and values derived for the dipole and quadrupole moments of Am^{241} and Am^{243}. Although the Am I and Am II term analyses are still quite incomplete it appears fairly certain that the low terms in each case are analogous to those of Eu as previously suggested.[1] Many of the strong spark lines with wide hfs have patterns indicating comparable splittings in both upper and lower states, from which the ground $5f^77s\ {}^9S_4$ and ${}^7S_3$ structures can be determined directly. Within experimental error both terms obey the interval rule exactly for $J=4$ and $J=3$, respectively, giving another confirmation of the presence of S states from an f^7 core.

TABLE I. Hyperfine structure and nuclear moments of Am^{241} and Am^{243}.

Am II $5f^77s$	$A({}^9S_4)=+(79.5\pm1.0)\times10^{-3}$ cm^{-1}
	$B({}^9S_4)=-(0.027\pm0.02)\times10^{-3}$ cm^{-1}
	$A({}^7S_3)=-(88.1\pm0.9)\times10^{-3}$ cm^{-1}
	$B({}^7S_3)=+(0.002\pm0.01)\times10^{-3}$ cm^{-1}
	$\sigma(5f^7)=-(4.3\pm0.7)\times10^{-3}$ cm^{-1}
	$a(7s)=+(666\pm6)\times10^{-3}$ cm^{-1}
Am I $5f^77s7p$	$A({}^{10}P_{9/2})=+(57.8\pm0.1)\times10^{-3}$ cm^{-1}
	$B({}^{10}P_{9/2})=-(0.12\pm0.01)\times10^{-3}$ cm^{-1}
	$A({}^{10}P_{7/2})=+(48.0\pm0.1)\times10^{-3}$ cm^{-1}
	$B({}^{10}P_{7/2})=+(0.054\pm0.001)\times10^{-3}$ cm^{-1}
	$\mu_{241}=+1.4$ nuclear magnetons
	$Q_{241}=+4.9\times10^{-24}$ cm^2
	$\mu_{241}/\mu_{243}=+1.00\pm0.01$
	$Q_{241}/Q_{243}=+1.00\pm0.01$

On the other hand the intense arc lines λλ 6054 and 6405 have simple flag patterns with considerable deviation from the interval rule, corresponding to $J=9/2$ and $7/2$, respectively, and supporting the assumption that these lines are transitions from $5f^77s7p\ {}^{10}P_{9/2}$ and ${}^{10}P_{7/2}$ to the unsplit $5f^77s^2\ {}^8S_{7/2}$ ground state. Following the treatments of Schmidt[2] and Casimir[3] we derive the values shown in Table I, where

$$\Delta T=\tfrac{1}{2}AK+B[K(K+1)-(4/3)I(I+1)\cdot J(J+1)],$$
$$K=F(F+1)-I(I+1)-J(J+1),\quad I=5/2.$$

The values of A and B were calculated from measurements on the Am^{241} exposures. While the Am^{243} exposures were too light to permit a complete evaluation of the A's and B's, corresponding intervals in Am^{241} and Am^{243} patterns were measured and compared to obtain the ratios of the moments.

The dipole moments were calculated from the Goudsmit-Fermi-Segrè formula assuming $n^3=10$ and $d\sigma/dn=0$; this procedure introduces an uncertainty of perhaps 10–20 percent in addition to the uncertainties in the splittings listed in Table I. There is a further uncertainty in the case of the quadrupole moments owing to possible perturbations from other terms, although this appears unlikely because both P terms give essentially the same value. No Sternheimer correction was applied to the Q's. The uncertainty in the use of the conventional formulas for so heavy an atom is impossible to estimate.

The dipole moments correspond to an odd $f_{5/2}$ proton, but the quadrupole moments have the wrong sign for a single particle, and equal Q's are somewhat unexpected.

[†] Based on work performed under the auspices of the U. S. Atomic Energy Commission.

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