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Proton-Triton Elastic Scattering below 1 MeV*

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Cross sections for proton-triton elastic scattering have been measured between 163- and 520-keV c.m. energy for a scattering angle of 120° c.m. A hydrogen gas target was bombarded with tritons accelerated by an electrostatic generator. Recoil protons emerging at a laboratory angle of 30° were analyzed with a 16-in. radius, 180° double-focusing magnetic spectrometer. The cross section is 180 mb/sr at 163 keV, rises to a broad maximum of 240 mb/sr near 275 keV, and falls gradually to a value of 207 mb/sr at 520 keV. The standard deviations in the absolute cross sections range from 4 to 9%. The energy region studied here includes the region of excitation in the compound nucleus, He^4, in which there has been evidence for a 0^+ excited state. The implications of the present results for the question of the existence of an excited state of He^4 will require a theoretical analysis of the data. A search for monopole electron pairs from a $0^+ \rightarrow 0^+$ transition was made with indeterminate results.

I. INTRODUCTION

CROSS sections for the elastic scattering of protons by tritons have been measured in this laboratory by Hemmendinger, Jarvis, and Taschek,[1] by Ennis and Hemmendinger,[2] and by Jarmie and Allen.[3] Those and other measurements were concerned with proton energies from just below the threshold (1.02 MeV) for the reaction $T(p,n)He^3$ to energies of several MeV. Frank and Gammel[4] have made a phase-shift analysis of data in this region. The only data available below a proton energy of 700 keV are several determinations of Balashko[5] below 177 keV and measurements by Baumann[6] whose particle energies were poorly defined.

Interest in the proton-triton scattering cross section below the He^3+n threshold was renewed by the recent experiments of Lefevre, Borchers, and Poppe and of Poppe, Holbrow, and Borchers[7]; and their analysis by Werntz[8] concerning a possible virtual state of He^4 at an excitation energy near 20 MeV. These experiments were concerned with a study of the neutron spectra from the reaction $T(d,pn)T$ and revealed a pronounced maximum near the high-energy end of the neutron spectra which can be interpreted as a correlation of the proton and triton in a virtual state of He^4. The excitation energy of this state was determined to be 20.1 MeV, corresponding to an energy of 300 keV in the proton-triton center-of-mass system or to a proton energy of 400 keV in $T(p,p)T$ scattering. The question of a possible state at this energy has also been considered elsewhere.[3] The region of interest is shown in Fig. 1.

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[1] A. Hemmendinger, G. A. Jarvis, and R. F. Taschek, Phys. Rev. **76**, 1137 (1949).

[2] M. E. Ennis and A. Hemmendinger, Phys. Rev. **95**, 772 (1954).

[3] N. Jarmie and R. C. Allen, Phys. Rev. **114**, 176 (1959).

[4] R. M. Frank and J. L. Gammel, Phys. Rev. **99**, 1406 (1955).

[5] Y. G. Balashko, I. Y. Barit, and Y. A. Goncharov, Zh. Eksperim. i Teor. Fiz. **36**, 1937 (1959) [translation: Soviet Phys.—JETP **9**, 1378 (1959)].

[6] G. Baumann, J. Phys. Radium **18**, 337 (1957).

[7] 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).

[8] C. Werntz, Phys. Rev. **128**, 1336 (1962).

The present experiment was undertaken to investigate this region of excitation in He^4 by measuring the proton-triton elastic scattering as a function of energy. A search for high-energy electron pairs from the transition to the ground state from a possible 0^+ state was also made.

II. EXPERIMENTAL

Since it was desirable to determine the proton-triton scattering cross section at center-of-mass energies below 300 keV, a useful method was to bombard a hydrogen target with accelerated tritons. The c.m. energy was then $\frac{1}{4}$ of the laboratory triton energy and it was experimentally feasible to extend the measurements down to 650-keV triton energy or 163 keV in the c.m. system. This lower limit was set by difficulty in current integration of the triton beam because of severe multiple scattering in the target gas and in the entrance and exit foils of the gas target.

The kinematics of the scattering process $H(t,t)H$ confined the scattered tritons to a cone of half-angle $\sim 20°$ (lab) so that it was more convenient with our

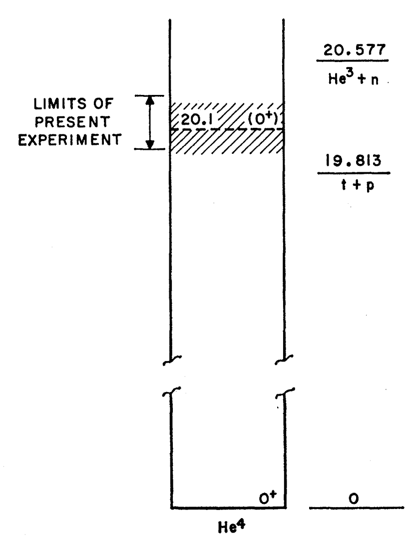

FIG. 1. Energy-level diagram of He^4. Energy is plotted vertically in MeV, with the ground state as 0. Note break in scale. Position of possible 0^+ level at 20.1 MeV is shown (see reference 8).

equipment to observe the recoil protons. The angle chosen was 30° (lab) which corresponded to the protons being ejected at 60° (c.m.) relative to the incident triton direction or to a c.m. angle of 120° for the scattering of either particle relative to its own initial direction.

The details of our experimental equipment have been described in several previous reports.[9] A beam of tritons in the energy range from 0.7 to 2.1 MeV was provided by a 3-MeV electrostatic generator. The triton beam entered the gas target through a thin (80 $\mu g/cm^2$) Pyrex glass window, passed through 8.6 cm of hydrogen gas at pressures of from 5 to 40 mm Hg, and, leaving the target through a thin Al foil, entered a Faraday cup for current integration. A second thin glass window at 30° (lab) allowed scattered recoil protons to enter the slit system of a 16-in. radius, 180° double-focusing magnetic spectrometer for momentum analysis and, finally, detection by a CsI scintillator at the spectrometer exit.

The error in the triton beam energy was less than 5 keV. The standard deviation in the central scattering angle (c.m.) was ±0.4°. The mean width of the angular acceptance of the spectrometer was ±1.5°. Other sources of error are discussed in reference 9.

This system has been used extensively in the past[9] so that its characteristics are well known and absolute cross sections can be measured with an accuracy of several percent. In the present experiment the proton-triton scattering cross sections have been normalized to the proton-proton scattering cross section at a proton energy of 1.00 MeV, the value of which was taken[10] to be 0.438 b/sr at 30° lab.

The target gas was analyzed mass spectrometrically and found to be 99.3 at.% hydrogen. Under the ion source conditions used, the triton beam (mass-3, singly charged) contained negligible amounts of contaminant particles [H_3^+, HD^+, and $(He^3)^+$].

A major problem below a bombarding energy of 1000 keV was multiple small-angle scattering of the triton beam in the target gas and in the entrance and exit windows of the target. At the lowest energies this scattering was severe enough to seriously hamper current integration of the beam by scattering a large fraction of the beam away from the Faraday cup. The multiple scattering corrections applied to the $H(t,p)T$ cross sections are listed in Table I. These corrections were obtained by using the $Ar(t,t)Ar$ elastic scattering cross section, assumed to be pure Rutherford scattering, as a reference. First, the effect of multiple scattering in the target *gases*, H_2 or Ar, was made negligible by reducing the gas pressures below the point at which the pressure had an effect on the measured cross sections. Then the correction for multiple scattering in the *windows* was obtained by comparing the measured $Ar(t,t)Ar$ cross sections to those calculated for Rutherford scattering. Since the triton beam energies at the entrance and exit windows were the same for the $Ar(t,t)Ar$ measurements as for the $H(t,p)T$ measurements and the effect of multiple scattering in the gases was negligible, this method should provide a reliable correction factor.

TABLE I. Correction for multiple scattering of the triton beam in the target windows. This effect reduces the measured beam current and thus increases the apparent cross section. The raw data are divided by this factor to give the corrected cross section.

Lab triton energy (keV)	Correction factor
650	2.85±0.2
700	1.72±0.1
800	1.21±0.05
900	1.09±0.03
≥1000	1.00±0.02

III. RESULTS AND DISCUSSION

Figure 2 and Table II show the data obtained in the present experiment, together with cross-section measurements at 132 and 88 keV (c.m.) by Balashko[5] and several points determined by Ennis and Hemmendinger[2] near 750 keV. Our values are in the region from 163 to 520 keV and join smoothly to the results at higher and lower energies. The line through the data points was drawn to indicate the trend of the cross section

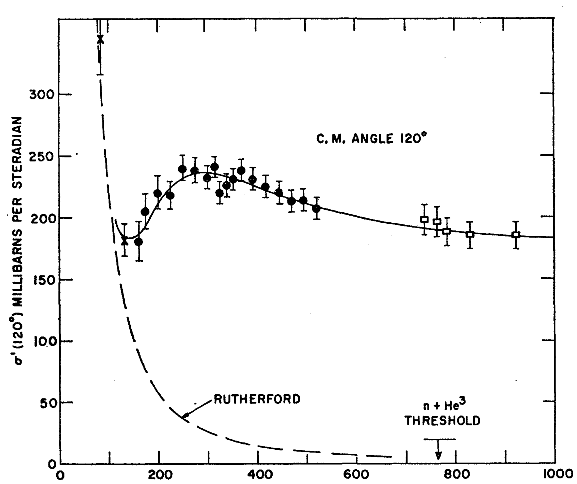

FIG. 2. Experimental results for $H(t,p)T$ c. m. differential cross section vs energy available in c.m. system. Solid circles: this experiment; hollow squares: reference 2; crosses: reference 5. Error bars indicate absolute standard deviations. The arrow indicates the threshold of the $T(p,n)He^3$ reaction. To change to triton beam lab energy or equivalent proton beam energy, multiply E' by 3.994 or 1.334, respectively.

[9] N. Jarmie and R. C. Allen, Phys. Rev. **111**, 1121 (1958); N. Jarmie and M. G. Silbert, *ibid* **120**, 914 (1960); M. G. Silbert and N. Jarmie, *ibid.* **123**, 221 (1961); D. B. Smith, N. Jarmie, and A. M. Lockett, *ibid.* **129**, 785 (1963).

[10] Los Alamos Report LA-2014 (unpublished); "Charged Particle Cross Sections," edited by N. Jarmie and J. D. Seagrave, available from Office of Technical Services, U. S. Dept. of Commerce, Washington, D. C.

TABLE II. Center-of-mass differential cross section for triton-proton scattering for a c.m. angle of 120°. Errors given are absolute standard deviations. E_t is the lab triton bombarding energy and $E_{c.m.}$ is the available energy in the center-of-mass system.

Source	E_t (keV)	$E_{c.m.}$ (keV)	$\sigma'(120°)$ (mb/sr)
Present experiment	650	163	181±16
	700	175	205±14
	800	200	220±13
	900	225	218±11
	1000	250	240±10
	1100	275	238±10
	1200	300	232±9
	1265	317	241±10
	1300	325	220±9
	1365	342	226±9
	1400	351	231±9
	1470	368	238±9
	1570	393	231±9
	1670	418	225±9
	1775	444	220±9
	1875	469	213±9
	1975	495	214±9
	2080	521	207±9
Reference 2		741	198±12
		764	196±12
		786	188±11
		830	185±11
		926	185±11
Reference 5		88	345±30
		132	182±13

and had no theoretical significance. The estimated standard deviation in the absolute value of each data point is indicated by the error bar. Relative errors in the present data are slightly smaller than the indicated absolute errors, being 3% for energies above 250 keV (c.m.).

The calculated Rutherford scattering cross section is shown by a dashed line. An advantage of the large scattering angle (120° c.m.) is the relatively minor contribution of Rutherford scattering over most of the region of interest.

The results of the present experiment show that the triton-proton scattering cross section at 120° slowly increases as the c.m. energy is decreased below the He^3+n threshold, from a value of 190 mb/sr at 750 keV to a maximum value of 240 mb/sr near 275 keV, and goes through a minimum value of about 180 mb/sr at 150 keV. It then increases rapidly as the Rutherford cross section dominates.

The shape of the curve resembles what one might expect from Coulomb-nuclear interference. These results should bear directly on the theoretical analysis of the $p-t$ interaction and its implications about the structure of He^4.

IV. SEARCH FOR MONOPOLE ELECTRON PAIRS

Assuming the existence of a 0^+ state near 20 MeV in He^4, there exists the possibility of electron pair emission from the $0^+ \to 0^+$ transition to the ground state. Electron pair emission may occur[11] with any order of electromagnetic transition, but is most noticeable in the light elements when gamma rays are forbidden. Pair emission probabilities also rise with the energy of transition.

A counter telescope using plastic scintillators with conventional electronics was set up to search for such very high-energy electrons. To avoid background problems, a tritium gas target was bombarded with an 800-keV proton beam. The target was "thick," absorbing all the energy of the beam, in order to intensify the pair production as much as possible. The cross section was estimated to be about 10^{-33} cm^2—its small size due in part to the competition of the heavy-particle elastic channel. Cosmic rays created a noticeable background. The effect of pairs produced in the target walls by gamma rays was overcome.

We observed at 0° about 10 electrons per second above 10 MeV, which was compatible with the estimated monopole pair cross section. However, a rough angular distribution indicated that these electrons are probably internal pairs associated with the electric dipole transition of the $T(p,\gamma)He^4$ reaction. An approximate calculation indicates that the dipole pair rate is also in rough agreement with the observed counting rate.

The result of the search for monopole pairs is, thus, indeterminate. A more elaborate experiment with two telescopes taking advantage of the somewhat different angular correlation[11] of the monopole pairs as compared to the dipole pairs could be tried, but would probably be quite difficult considering the low cross sections and the background problem. A possible corollary experiment of interest would be the measurement of the "internal pair conversion coefficient" for the dipole transition.

ACKNOWLEDGMENT

We are indebted to George I. Kachen for his skillful assistance in the search for monopole electron pairs.

[11] For a summary of this subject and a guide to the references see: E. Segrè, *Experimental Nuclear Physics* (John Wiley & Sons, Inc., New York, 1959), Vol. 3, p. 365 and 371; K. Siegbahn, *Beta- and Gamma-Ray Spectroscopy* (Interscience Publishers, Inc., New York, 1955), p. 636.