2.L

Nuclear Physics **A174** (1971) 399—407; © *North-Holland Publishing Co., Amsterdam*

THE ELASTIC SCATTERING REACTIONS ^{4}He(t, t)^{4}He AND ^{4}He(τ, τ)^{4}He NEAR 2 MeV

L. S. CHUANG

Chung Chi College, The Chinese University of Hong Kong, Hong Kong

Received 2 July 1971

Abstract: A Van de Graaff accelerator and a nickel foil isolated gas scattering chamber are used for elastic scattering of tritons and τ-particles by ^{4}He. Angular distributions are measured for $E_t = 2.98$, 2.46 and 2.13 MeV, and $E_\tau = 2.98$, 2.46 and 1.72 MeV over an angular range from 34.9° to 136.9° in the c.m. system. Computer extraction of the phase shifts using the partial waves up to $l = 1$ is undertaken. Comparisons of the present results with the available published results are made. A new method of beam collection by a Faraday cup in the target gas is attempted. The method is correct to ± 4 % under the present experimental conditions.

E | NUCLEAR REACTIONS ^{4}He(t, t), $E = 2.98$, 2.46 and 2.13 MeV; ^{4}He(^{3}He, ^{3}He), $E = 2.98$, 2.46 and 1.72 MeV; measured $\sigma(E; \theta)$; deduced phase shifts. Gas target.

1. Introduction

In recent years, the cluster model has been extensively used for the analysis of scattering problems where both the incident and the target nucleus are composed of only a few nucleons. For the mirror pair, ^{7}Li and ^{7}Be, the states can be checked with comparative ease for the cluster model prediction.

Measurements of the elastic scattering of τ-particles by ^{4}He with the incident τ-energy in the range of 2.97 to 5.5 MeV in the lab system have been made by Miller and Phillips [1]. From the scattering data of Miller and Phillips, the expected cluster form of the $\frac{7}{2}^-$ state and the α-particle plus mass-3 cluster form of the ground and first excited states of the nucleus ^{7}Be are shown.

On the other hand, with phase-shift analysis, Miller and Phillips showed that the S-wave scattering can be described by a hard-sphere interaction while the P-wave scattering can be described by a bound-state plus hard-sphere interaction. Later, Tombrello and others [2, 3] extended the region of the incident τ-energy up to 18 MeV and observed the $\frac{5}{2}^-$ level of $l = 3$ spin-orbit doublet in addition to the known $\frac{7}{2}^-$ level, and also other $\frac{5}{2}^-$ and $\frac{7}{2}^-$ levels. In the meantime, using an improved experimental technique, Barnard *et al.* [4]) repeated the measurement of Miller and Phillips. They confirmed, with better accuracy, the previous findings, but found that the phase shift for P-wave scattering, δ_1^-, cannot be explained solely by the effect of ^{7}Be first excited state.

Theoretical prediction shows essentially the same level structure for the low-lying states of ^{7}Li and ^{7}Be [ref. [5]]. The differential cross sections for the elastic scattering of tritons by ^{4}He, with the incident energy at 1.71 and 2.15 MeV, are reported by Hemmendinger [6]. Allen and Jarmie [7], however, have pointed out that the differential cross sections obtained by Hemmendinger are 21 % higher than their value, obtained at one point of measurement, for the incident triton energy of 1.677 MeV. Recent measurements of the elastic scattering of ^{4}He by tritons, carried out by Spiger and others [3], cover the energy range from 4 to 18 MeV.

The intention of the present work is to extend the angular distribution measurements to the unexplored region near 2 MeV, and to test the phase shifts calculated by Brown and Tang [8]. It is worth noting that the extension of the measurements of the elastic scattering to the low-energy region is useful for the phenomenological analysis of the ^{3}H$(\alpha, \gamma)^7$Li and ^{3}He$(\alpha, \gamma)^7$Be reactions [9], in which equal radii for the hard-sphere interaction in the S-state both for ^{3}H-^{4}He and ^{3}He-^{4}He system are assumed.

2. Experimental procedure

2.1. GENERAL

Singly charged mass-3 ion beams are provided by the Nippon Atomic Industry Group 4.23 MeV Van de Graaff accelerator. The precision of the particle energies during the time of the experimental measurements is better than 0.2 %. The beam current of several μA, after the selection of the beam analyzing magnet, can be brought to the target center situated about 9 m away from the beam analyzer. The beam collimation and defining system is designed in such a way as to define the diverging beam emerging from the Q-magnet to about 5 mm diameter at the target center.

The scattering chamber is filled with ^{4}He gas. A Ni foil of 0.5 μm thickness is pasted on the beam entrance to the chamber. The beam cross section at the entrance to the Faraday cup of 30 mm diametric opening, tested with a photo-sensitive paper, is 10 mm diameter. Therefore if no further obstacle is present, such as another Ni foil on the entrance to the Faraday cup, apart from the ^{4}He gas layer of pressure around 10 mm of Hg used presently, it is certain that 100 % of the incident beam particles will be received by the Faraday cup.

An estimate of the energy loss of the incident beam particles, in passing through the Ni foil pasted at the entrance to the scattering chamber and the ^{4}He gas layer between the entrance and the target center, is made using the data from ref. [10]. It is thus found that the beam energy at the scattering center has an uncertainty of about 1 %.

The Faraday cup is fixed in place and can be used either in the target gas or in a vacuum by pasting a Ni foil on the entrance to the cup. In view of the success obtained in the test by using a Faraday cup in the target gas [11], this method has been retained for the principal part of the experiment.

A goniometer carries two radial arms on which the detector systems are seated and which can be separately rotated, over an angular range of 6° to 150°, with an angular resolution of ±0.5°. One of the two detectors is rotated to cover the whole angular range of interest, while the other one is fixed at 40° and used as a monitor.

The detectors used are silicon surface-barrier type with a depletion layer of about 60 μm, thick enough to completely stop the particles being studied. Charges created in the detectors are amplified with charge-sensitive preamplifiers, and the positive pulses are inverted before feeding into the respective "inputs" of the Technical Measurements Corporation 400-channel pulse-height analyzer. The resolution of the spectral peaks, in FWHM at the forward directions, are 50 and 90 keV, respectively, for t-^{4}He and τ-^{4}He scattering. The most forward-angle measurable for the various incident energies of t-^{4}He and τ-^{4}He scattering is 20° in the lab system except for the incident τ-energy 1.72 MeV.

The target gas is ^{4}He gas of pressure around 10 mm of Hg. The ^{4}He gas of chemical purity is further purified by passing it through a charcoal trap embedded in liquid nitrogen. The charcoal used as the purifier is reheated from time to time, under 200° C in vacuum for about 20 min, with the pumps operating. The chamber gas is discharged and the chamber refilled with fresh gas before the pressure indicated by the manometer shows a change of a few %. In this way the readings of the pressure are estimated to be better than ±0.7 %. The chamber gas temperature is read from a thermometer placed directly above the target center on the chamber lid. Readings of the pressure and temperature are made before and after each measurement of the angular distribution, and the average values are taken for the calculation of the density of the target nuclei.

2.2. MEASUREMENT OF BEAM CURRENT

In the measurement of the beam charge, a Faraday cup is used in the ^{4}He gas. The current integrator of Higinbotham and Rankowitz type is incorporated into the beam current recording system. The accuracy of the measured quantity of charge by the system is estimated to be about 0.6 %.

To test the validity of using a Faraday cup in the target gas, ^{4}He, of pressure around 10 mm of Hg, the following procedures are used: Two silicon surface-barrier-type solid-state detectors, with the sensitive area well defined, are used as the monitors. They are fixed at laboratory angles of 20° (for t-^{4}He scattering) and 50° (for τ-^{4}He scattering) in the scattering chamber filled with ^{4}He gas. Triton and τ beams are accelerated to 2.13 and 2.98 MeV, respectively, and the elastic scattering of t-^{4}He and τ-^{4}He is studied at various target gas pressures ranging from 0.6 to 13.2 mm of Hg. Exposures of the target to the accelerated particles are continued till a monitor counting statistic of about 3 % is attained. The result of each test measurement is expressed in terms of a value A, expressing the number of monitor counts per unit pressure and unit current integrator reading. The values of A are plotted on the ordinate and the gas pressures on the abscissa of fig. 1. Lines with practically zero slope are plotted to fit the experimental points by a least-squares procedure. The estimated fractional standard deviation for the value A is about $\pm 4\ \%$. The constancy of the values A for different pressures extending down to the pressure 0.6 mm of Hg, and possibly to zero pressure, is a satisfactory proof of the

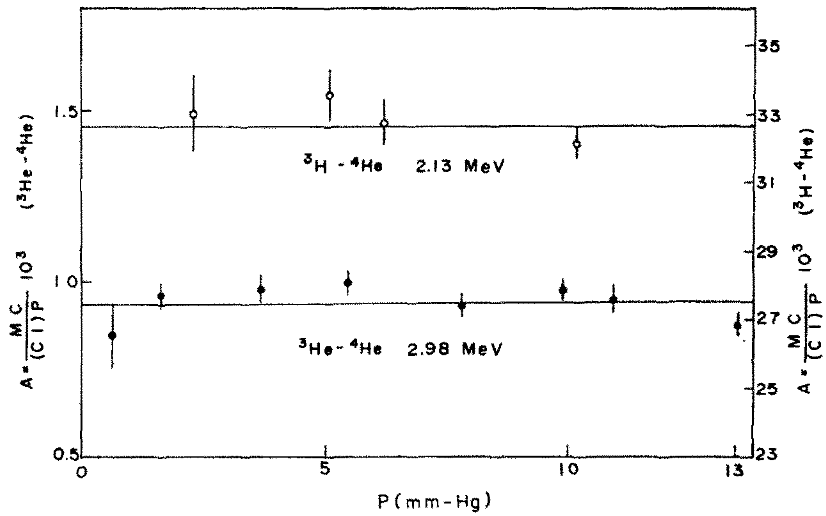

Fig. 1. The values of A i.e. the number of monitor counts (M.C.) per unit pressure (P) and unit current integrator reading (C.I.) versus Faraday cup pressures. The open circles are the results for t-^{4}He scattering at $E_T = 2.13$ MeV and the closed circles are those of τ-^{4}He scattering at $E_\tau = 2.98$ MeV.

validity of using the Faraday cup in the ^{4}He gas for recording accelerated particles. This is true at least under present experimental conditions. More details are given in a separate article [11]).

To test further the correctness of the above method, data of the elastic scattering of τ-particles by ^{4}He, at the forward angles, for the incident energy at 2.45 MeV are taken using an admixture of ^{4}He and Xe as the target gas. Differential cross sections deduced from the known Coulomb scattering for the τ-Xe scattering are in agreement with those obtained with the beam current measured according to the above method. (The angular distribution of τ-^{4}He scattering at 1.72 MeV is measured with an admixture of ^{4}He and Xe as the target gas.) This result, therefore, can be thought of as further support for the conclusion made regarding the use of a Faraday cup in the ^{4}He gas.

2.3. DETECTOR SYSTEM

A slit system, of rectangular shape for both the front and rear slits, is used to define the scattered particles. The so-called G-factor is given by

$$G = \frac{2b_1 2b_2 h}{R_0 l},$$

where $2b_1$ and $2b_2$ are the widths of the front and rear slits, respectively, h is the height of the rear slit, l is the separation of the slits, and R_0 is the distance between the target center and the rear slit. The G-factor in the present measurements is 1.49 μm.

In the estimation of the differential cross section from the yield at each scattering angle, the correction due to the finite size of the incident beam and the detector system is made [13]). It amounts to 0.7 % at 20°, 0.5 % at 25°, and 0.3 % at 30°.

In order to avoid the pile-up of the electronic circuit of the counting system, the beam-current is limited to less than 0.05 μA. Under these conditions the counting rate is within about 10 counts per s, so that a correction for the counting loss of the pulse-height analyzer is unnecessary. For any given angle of measurement, exposure of the beam lasts for a period of time such that the counting statistic is about 3 %. In the backward angles, however, a period of exposure longer than 60 min is necessary for 3 % counting statistics. In order to avoid accidental errors being introduced into the counting through unduly long period of exposure, repeated runs with each period of exposure shorter than 30 min are attempted.

To see the background contribution to the actual countings, the scattering chamber is evacuated and angular distribution measurements are undertaken for incident tritons and τ-particle energies at 2.13 and 2.98 MeV, respectively. The results of the measurements show a negligible background.

Correct identification of the energy peaks under study is made by comparison of the corresponding kinematics curves obtained by the experiment and by calculation. The counts of recoil ^{4}He in the forward angles are converted into the corresponding scattered triton or τ-particle in the backward directions in the c.m. system.

3. Results and discussion

Results of the measured angular distribution are listed in tables 1 and 2. In terms of the original quantities measured for the calculation of the differential cross sections,

TABLE 1

The t-^{4}He angular distribution

E_{lab} = 2.13 MeV			E_{lab} = 2.46 MeV			E_{lab} = 2.98 MeV		
$\theta_{c.m.}$ (deg)	dσ/dΩ (mb/sr)	Δ(dσ/dΩ) ±(%)	$\theta_{c.m.}$ (deg)	dσ/dΩ (mb/sr)	Δ(dσ/dΩ) ±(%)	$\theta_{c.m.}$ (deg)	dσ/dΩ (mb/sr)	Δ(dσ/dΩ) ±(%)
34.9	770	6	34.9	667	6	34.9	538	6
43.6	533	6	43.6	413	6	43.6	376	6
54.7	302	6	54.7	262	5	54.7	246	5
63.4	192	5	63.4	179	5	63.4	178	5
69.8	153	5	69.0	143	5	69.0	136	5
85.3	89	5	85.3	74	6	85.3	75	6
105.9	35.0	5	105.9	27.3	7	105.9	24.9	7
116.8	29.6	10	116.8	15.2	9	116.8	17.1	6
129.3	27.2	10	129.3	11.0	11	129.3	10.8	8
136.9	26.3	7						

TABLE 2

The τ-^{4}He angular distribution

$E_{lab} = 1.72$ MeV			$E_{lab} = 2.46$ MeV			$E_{lab} = 2.98$ MeV		
$\theta_{c.m.}$ (deg)	$d\sigma/d\Omega$ (mb/sr)	$\Delta(d\sigma/d\Omega)$ $\pm$(%)	$\theta_{c.m.}$ (deg)	$d\sigma/d\Omega$ (mb/sr)	$\Delta(d\sigma/d\Omega)$ $\pm$(%)	$\theta_{c.m.}$ (deg)	$d\sigma/d\Omega$ (mb/sr)	$\Delta(d\sigma/d\Omega)$ $\pm$(%)
40.1	1680	2.5	34.9	1340	6	34.9	1200	6
43.6	1200	3	43.6	671	6	43.6	550	6
52.1	700	3	54.7	324	5	54.7	260	5
60.6	400	1.4	63.4	209	6	63.4	173	5
69.0	257	4	69.0	155	5	69.0	137	5
77.2	194	1.4	85.3	81	6	85.3	66	6
85.3	142	2.3	105.9	45	7	105.9	26.8	6
93.1	104	9	116.8	38	7	116.8	18.9	8
100.7	105	10	129.3	35	7	129.3	17.5	6
108.1	101	6	136.9	30	7	136.9	16.0	6
115.1	100	9						

the fractional standard deviation for the differential cross section at Ψ_{lab}, $S_{\sigma(\Psi_{lab})}$, can be calculated from the individual independent sources of error by

$$S_{\sigma(\Psi_{lab})} = (S_e^2 + S_R^2 + S_T^2 + S_{C_D}^2 + S_{\sin\Psi_{lab}}^2 + S_Q^2 + S_{N_0}^2 + S_G^2)^{\frac{1}{2}},$$

where S is the fractional standard deviation of the quantity indicated as the suffix, with $e \equiv$ electronic charge, $R \equiv$ the ideal-gas constant, $T \equiv$ absolute temperature of the chamber gas (K), $C_D \equiv$ detector counts for the quantity of accumulated beam charge Q, $N_0 \equiv$ Avogadro's number, and $G \equiv$ the G-factor. Errors of the measured differential cross sections caused by $\pm 0.5°$ uncertainty in angular resolution of the

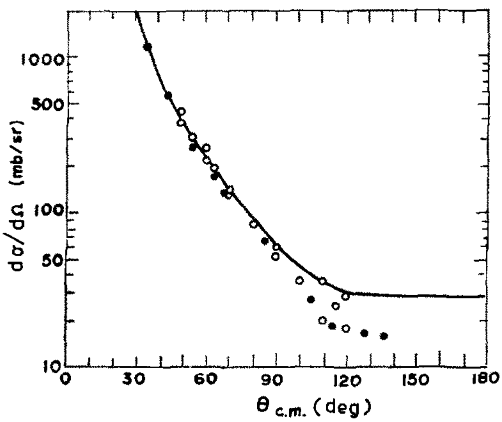

Fig. 2. Angular distribution for τ-^{4}He scattering at $E_\tau = 2.98$ MeV ($E_{c.m.} = 1.70$ MeV). The closed circles are the present result. The open circles are the results of Miller and Phillips [1]) and the solid curve is that calculated by Brown and Tang [8]).

detector position are estimated and added into the overall error attached to the differential cross sections in the tables.

The measured angular distributions of t-^{4}He scattering for E_t = 2.13 MeV are compared with the published data. The present results are in good agreement with the published results [6]) in the angular range from $\theta_{c.m.}$ = 80° to 137°. In the forward

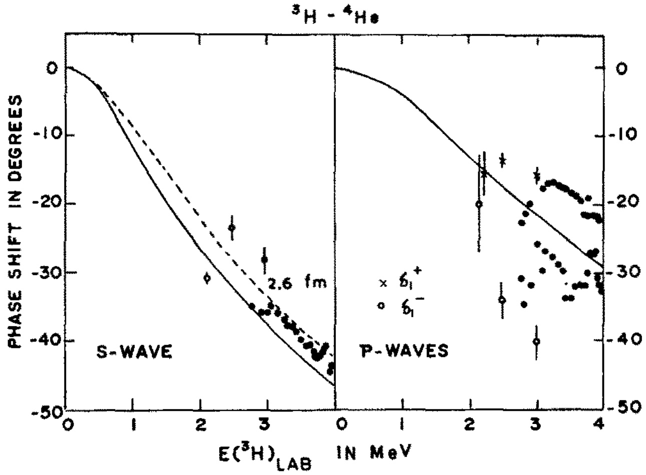

Fig. 3. The S- and P-wave experimental phase shifts for t-^{4}He scattering, as a function of bombarding energy. The crosses and open circles are from the present experiment. The solid curves are calculated by Brown and Tang [8]), using the resonant group method. The dashed curve is calculated using hard-sphere scattering for radius 2.6 fm. The closed circles are the results of Spiger and Tombrello [3]).

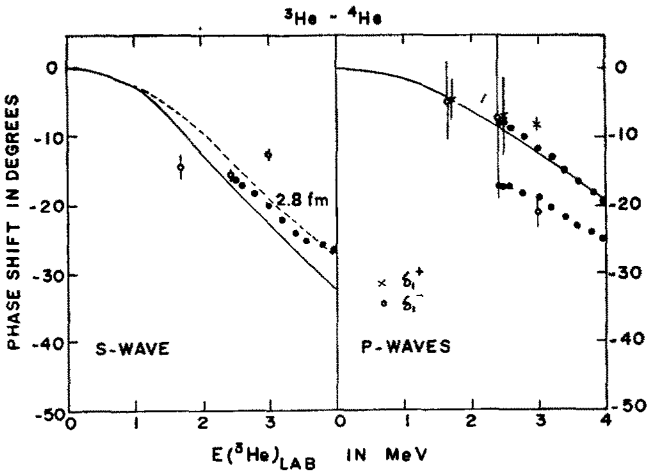

Fig. 4. The S- and P-wave experimental phase shifts for τ-^{4}He scattering, as a function of bombarding energy. The crosses and open circles are from the present experiment. The solid curves are calculated by Brown and Tang [8]), using the resonant group method. The dashed curve is calculated using hard-sphere scattering for radius 2.8 fm. The closed circles are the results of Barnard *et al.* [4]).

direction, however, the present result is about 25 % less than the published result.

The present results on the angular distributions of τ-^{4}He scattering are compared with those published for $E_\tau = 2.46$ [ref. [4]] and 2.98 MeV [ref. [1]]. Agreement, within the experimental errors, between the two sets of angular distribution for $E_\tau = 2.46$ MeV is obtained. Detailed comparison for $E_\tau = 2.98$ MeV is shown in fig. 2, which indicates that the present results are systematically smaller, by the order of the present standard deviations, than the result of Miller and Phillips [1]. The full line in fig. 2 is the calculated differential cross section, by Brown and Tang [8], using the resonating group method.

A phase-shift analysis is made, taking S- and P-wave into account. A programme prepared by Okai [14] for the HARP-5020 computer installed in The University of Tokyo is used. The results are shown in figs. 3 and 4, together with the calculated phase shifts by Brown and Tang [8]. Solutions with $\delta(P^+) > \delta(P^-)$ are selected in considering the continuation from the solutions at higher incident energies [3,4], which are also shown in the figures with closed circles.

When S-wave phase shifts are compared with those of the hard-sphere scattering, the tendency of a smaller hard-sphere radius in t-^{4}He scattering than in τ-^{4}He scattering appears, as has already been noted in ref. [3]. The splitting between two P-waves is larger in t-^{4}He scattering than in τ-^{4}He scattering.

A slightly higher value of the present phase shift, δ_0 at 2.98 MeV in τ-^{4}He scattering, over the earlier work [1] is expected from the result of the smaller angular distribution of the present experiment than the earlier work, as discussed above. It looks as though the phase shifts in the present experiment tend to scatter somewhat. The only probable reason for this trend is in the use of a Faraday cup in target gas. Although the validity of the method is fully tested, as discussed in subsect. 2.2, the phenomena around the Faraday cup in target gas is a complex one. Therefore, it is questioned, without any justification, that there may be a few % more error. As emphasized earlier, the use of a Faraday cup in target gas is both simple and effective. It is hoped that a further study on the method can be made in the near future so that the method can be completely established.

The author wishes to thank Prof. J. Sanada for his advice, the members of the Tokyo University of Education and the Nippon Atomic Industry Group for the encouragements and assistance. He wishes also to acknowledge the grant given by the Chinese University of Hong Kong.

References

1) P. D. Miller and G. C. Phillips, Phys. Rev. **112** (1958) 2048
2) T. A. Tombrello and P. D. Parker, Phys. Rev. **130** (1963) 1112
3) R. J. Spiger and T. A. Tombrello, Phys. Rev. **163** (1967) 964;
M. Ivanovich, P. G. Young and G. G. Ohlsen, Nucl. Phys. **A110** (1968) 441
4) A. C. L. Barnard, C. M. Jones and G. C. Phillips, Nucl. Phys. **50** (1964) 629

5) D. Kurath, Phys. Rev. **101** (1966) 216;
J. M. Soper, Phil. Mag. **2** (1957) 1219;
L. D. Pearlstein, Y. C. Tang and K. Wildermuth, Nucl. Phys. **18** (1960) 23;
Y. C. Tang and K. Wildermuth, Phys. Rev. **123** (1961) 548;
A. B. Clegg, Nucl. Phys. **33** (1962) 194;
C. M. Chesterfield and B. M. Spicer, Nucl. Phys. **41** (1963) 675
6) A. Hemmendinger, Bull. Am. Phys. Soc. **1** (1956) 96
7) R. C. Allen and N. Jarmie, Phys. Rev. **111** (1958) 1129
8) R. E. Brown and Y. C. Tang, Phys. Rev. **176** (1968) 1235
9) T. A. Tombrello, Astrophysical problems in nuclear research with low energy accelerators, ed. J. B. Marion and D. M. Van Patter (Academic Press, New York, 1967) p. 195;
T. A. Tombrello and P. D. Parker, Phys. Rev. **131** (1963) 2582
10) C. Williamson and J. P. Boujot, Tables of range and rate of energy loss of charged particles of energy 0.5 to 150 MeV (Centre d'Etudes Nucléaires de Saclay, 1962)
11) L. S. Chuang, Nucl. Instr. **75** (1969) 171
12) W. A. Higinbotham and S. Rankowitz, Rev. Sci. Instr. **22** (1951) 688
13) C. L. Critchfield and D. C. Dodder, Phys. Rev. **75** (1949) 419;
H. R. Worthington, J. N. McCruer and D. E. Findley, Phys. Rev. **90** (1953) 899;
E. A. Silverstein, Nucl. Instr. **4** (1959) 53
14) S. Okai, private communication (1969)