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# Charge-Asymmetry Effects in the Reaction $^2$H($^4$He, $^3$He)$^3$H†

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Differential cross sections for the process $^2$H($^4$He, $^3$He)$^3$H are presented for $^4$He beam energies of 82.1, 64.3, and 49.9 MeV. The measurements were made to test the Barshay-Temmer theorem which requires $^3$H and $^3$He yields to be independently symmetric about 90° c.m. We find a pronounced deviation from 90° c.m. symmetry which is angle- and energy-dependent. A distorted-wave Born-approximation analysis assuming the reaction mechanism to be a simple $l=0$ nucleon-pickup process can qualitatively account for the observed deviations.

## I. INTRODUCTION

Recent determinations[1,2] of the $^1S_0$ scattering length of the $n$-$n$ system appear to limit deviations from charge symmetry of the nuclear force to less than 1%. The value of the $^1S_0$ scattering length for the $n$-$p$ system has been interpreted[3] as implying a breakdown in the charge independence of nuclear forces of a few percent. This near-perfect charge independence of nuclear forces has led to the isospin formalism for the classification of nuclear states. In this formalism, deviations from charge independence are ascribed to the action of the Coulomb force – the effects of which are, in principle, amenable to analysis.

Barshay and Temmer[4] have suggested an interesting geometric test of the isospin formalism for reactions of the type

$$A+B \rightleftharpoons C+C', \qquad (1)$$

where $C$ and $C'$ are members of the same isospin multiplet and either $A$ or $B$ has isospin 0. If isospin is a valid concept, the angular distribution of each reaction product must by symmetric about 90° c.m. The beauty of this test is apparent when one realizes that the equal masses of $C$ and $C'$ and the condition of symmetry about 90° c.m. leads to the equality of the yields of $C$ and $C'$ at the same laboratory angle. The measurement is thus reduced to the determination of the yields of $C$ and $C'$ under the same conditions and, in principle, is limited in accuracy only by counting statistics.

Conversely, the observation of $A$ and $B$ as reaction products requires the measurement of absolute cross sections to test the prediction of the "Barshay-Temmer" theorem. Although this method is inherently less accurate than the measurement of $C$ and $C'$ yields, Nam, Osetinskii, and Sergeev[5] have succeeded in making a careful experimental test of the theorem for the reaction $^3$He + $^3$H → $^4$He + $^2$H for several triton energies in the range 1–1.5 MeV. They report their angular distributions to be consistent with symmetry about 90° c.m. within the experimental limits of 1–1.5%. Using the simpler method of detecting isospin multiplet pairs, Fortune, Richter, and Zeidman[6] also report agreement with the "Barshay-Temmer" theorem for the reaction $^4$He + $^{10}$B → $^7$Be + $^7$Li at 33 MeV c.m. Von Oertzen *et al.*[7] have also detected isospin multiplet pairs in the reaction $^{14}$N + $^{12}$C → $^{13}$C + $^{13}$N at 36 MeV c.m. using a magnetic spectrometer. Corrections for different charge states and for the magnet calibration had to be made. They also report agreement with 90° symmetry except for two data points at the largest experimental angles. The first clear-cut violation of the "Barshay-Temmer" theorem was reported by Gross *et al.*[8] for the reaction $^4$He

$+{}^2H \rightarrow {}^3He + {}^3H$ at 27.4 MeV c.m. They found a diffraction-like pattern for the violation with deviations from 90° symmetry as much as 10%. Subsequently, a qualitative understanding of these effects was provided by simple distorted-wave Born-approximation (DWBA) analyses[9,10] and the effect was attributed to Coulomb-energy differences in the ${}^3$He and ${}^3$H bound-state form factors. A very recent study by Wagner, Foster, and Greenebaum[11] of this reaction at an incident $\alpha$-particle energy of 48.25 MeV also shows significant deviations from symmetry. Their deviations are as large as 20%.

To investigate the energy dependence of the isospin-conservation violations found[8] in the reaction ${}^2H({}^4He, {}^3He){}^3H$, we have extended the measurements to two other energies, 21.4 and 16.6 MeV in the incident channel c.m. system. For completeness, we include the earlier work at 27.4 MeV c.m. We also present DWBA analysis of the data which qualitatively accounts for both the angular and energy dependence of the effect.

## II. EXPERIMENTAL DETAILS

The $\alpha$ and deuteron beams used in this experiment were accelerated by the Oak Ridge isochronous cyclotron (ORIC) and magnetically analyzed for an energy spread of 0.28% full width. This beam was focused at the target position to a spot about 3 mm wide and 9 mm high with an angular divergence of ±0.3°.

The target consisted of a 7.8-cm-diam gas cell with a 2.5-mg/cm$^2$ Be entrance window and a 2.1-mg/cm$^2$ Havar exit foil. After emergence from the exit foil, the beam was stopped in a Faraday cup. Most of the data were taken with the gas cell filled with 300 Torr of 99.9% enriched deuterium gas cooled to 77°K. Check runs were also made with the gas cell filled with 300 Torr of deuterium at 294°K and with 300 Torr of 99.9% helium at 77°K. A pair of gold defining slits between the gas cell and the detectors fixed the scattering plane acceptance at 0.6° and the solid angle at $\sim 4 \times 10^{-5}$ sr. These slits were constructed with a thin polished edge to reduce, as much as practical, the slit-edge scattering.

Charged reaction products from the target were detected by a conventional $\Delta E$-$E$ telescope consisting of a 322-$\mu$ Si passing detector and a 2-cm-thick NaI stopping detector for the 82.1-MeV $\alpha$-beam data. A 3000-$\mu$-thick Si detector was used in place of the NaI for the 64.3- and 49.9-MeV $\alpha$-beam data. The check run involving a 41.0-MeV deuteron beam incident upon a ${}^4$He target required the use of an 87-$\mu$ Si passing detector. The thinner $\Delta E$ detector was also required for angles greater than 70° c.m. for the run with a 49.9-MeV $\alpha$-beam. Linear pulses from the stopping detector and the $\Delta E$ detector were gated by a coincidence requirement and routed to the $x$ and $y$ inputs, respectively, of a $200 \times 100$ channel analyzer. Dead time in the analyzer was determined in two independent ways. In one method, live time was measured by scaling a 1-kHz clock. The same clock was fed to another scaler which was gated by the busy signal of the analyzer. In the second method the number of legitimate coincidence signals routed to the analyzer were scaled as were the number of stored counts. The dead time derived from both methods usually agreed to better than 1%.

Absolute cross sections were obtained by normalization to known elastic scattering cross sections. To normalize the data for the 82.1-MeV experiment, we filled the gas cell with ${}^4$He, measured the elastic scattering yield at 37° c.m., and compared the results with the absolute measurements of Darriulat *et al.*[12] The 49.9-MeV data were normalized to the 24.85-MeV deuteron $d+{}^4$He elastic scattering data of Van Oers and Brockman[13] at 95° c.m. To normalize the data obtained with a 65-MeV $\alpha$ beam, we used the $d+{}^4$He elastic scattering data of Hammond, Morales, and Cahill.[14]

## III. RESULTS

Several important checks were made to demonstrate the validity of the data presented in this report. First, as mentioned in the previous section, the data were reproduced with target densities that differed by approximately a factor of 4. Secondly, the defining-slit geometry was changed to determine if there was any discernible slit-edge scattering effect. The third test was a geometric one based upon the requirement that the ratio of the observed yield of ${}^3He/{}^3H$ at 90° c.m. must be unity irrespective of charge symmetry. Finally, if the target and beam are interchanged such that the c.m. conditions remain unchanged, then the ratio of the yields should invert. By accelerating deuterons with the same cyclotron conditions as for the $\alpha$ beam and refilling the target cell with ${}^4$He, the proper c.m. requirements are automatically satisfied. The results of these checks were that, within the statistical uncertainty, the data were reproducible. Thus, we conclude that there are no systematic experimental biases in the experiment and, as expected, multiple-scattering effects were negligible.

The angular distributions and observed fore-aft asymmetries for the three incident energies studied are presented in Figs. 1–3. The statistical errors associated with the cross sections are smaller than the points in the figures. The error in the absolute cross section is more difficult to evaluate but is estimated to be less than 15%. The errors in the asymmetries reflect the statistical uncertainty in the ratio of the yields of $^3$He to $^3$H and the uncertainty in background subtraction. A correction has been applied to the observed triton yield to account for nuclear reactions in the stopping counter at the highest energies studied.[15] This effect is energy-dependent and was always less than 2%. The error which could be introduced by applying this correction was small in comparison with the statistical errors.

From inspection of the results presented in Figs. 1–3, it is clear that we find, at each energy studied, a pronounced and angle-dependent deviation from 90° symmetry for the exit-channel reaction products. The observed asymmetries are as large as 15–20% at some angles whereas the errors are typically less than 3%. The experimental differential cross sections show a marked, but not unexpected, variation with bombarding energy. As the incident energy is increased from ~50 to ~82 MeV, the angular distributions change from one characterized by a single maximum at 90° c.m. to one with a 90° peak and attenuated maxima at 45 and 135°, and finally to a distribution with three pronounced peaks at 45, 90, and 135°. It is, perhaps, worth noting that there appears to be a correlation between the slopes of the differential cross section and that of the fore-aft asymmetry ratio. That is, the ratio increases and decreases in the same angular ranges where the cross sections increase and decrease.

The asymmetry observed[11] at $E_\alpha = 48.25$ MeV has qualitatively the same shape as our data at $E_\alpha = 49.9$ MeV. They find that the fore-aft ratio is less than unity for angles between ~45° and 90°, as we do, and is greater than unity for angles

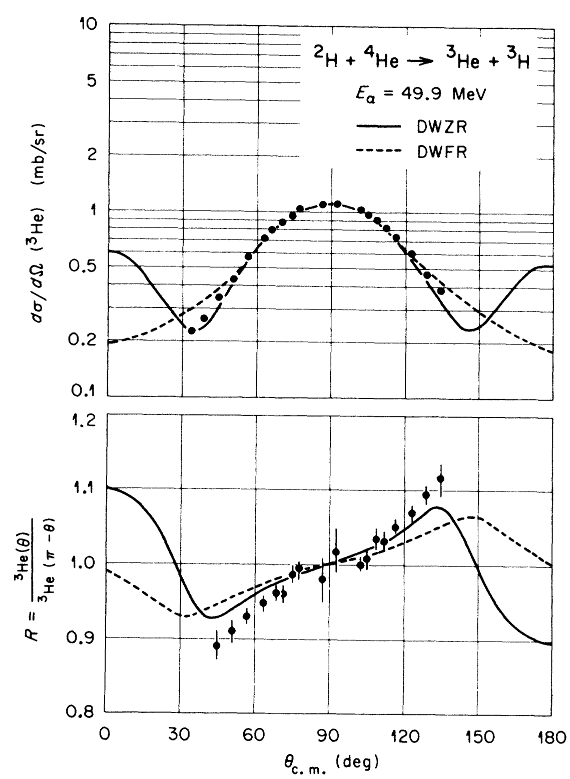


FIG. 1. In the upper half of the figure are shown the measured differential cross sections for $^3$He from the reaction $^4$He + $^2$H → $^3$He + $^3$H using a 49.9-MeV $\alpha$ beam. Relative errors are smaller than the size of the points. The angular dependence of the ratio of $^3$He to $^3$H yields is shown in the lower half of the figure. The solid curve is the prediction of a distorted-wave zero-range calculation and the dashed curve that of a distorted-wave finite-range calculation.

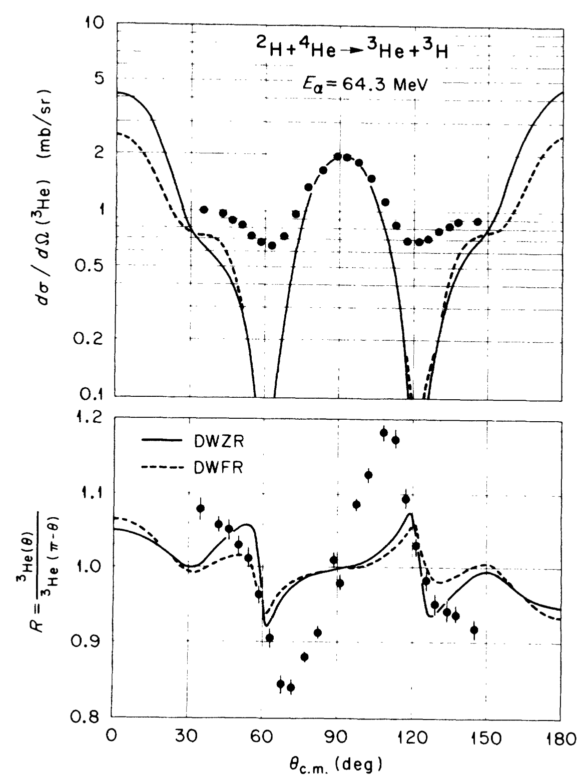


FIG. 2. In the upper half of the figure are shown the measured differential cross sections for $^3$He from the reaction $^4$He + $^2$H → $^3$He + $^3$H using a 64.3-MeV $\alpha$ beam. Relative errors are smaller than the size of the points. The angular dependence of the ratio of $^3$He to $^3$H yields is shown in the lower half of the figure. The solid curve is the prediction of a distorted-wave zero-range calculation and the dashed curve that of a distorted-wave finite-range calculation.

smaller than 40° which were not investigated here. Their data has roughly the same shape as the calculated asymmetry we present in the next section, but is larger in magnitude. There does appear to be an inconsistency in the 90° differential cross sections, however. The data of Ref. 5 show a smooth variation of the 90° cross section from ~0.6 mb/sr at a $^3$He-$t$ c.m. energy of 522 keV to ~0.75 mb/sr at 760 keV. The data presented in this paper also show a corresponding increase from ~1 mb/sr at 2.35 MeV (c.m.) to ~2.6 mb/sr at 13 MeV. The value quoted by Wagner, Foster, and Greenebaum[11] of 0.28 mb/sr at $E_{c.m.} = 1.76$ MeV is apparently low by a factor of almost 3.

## IV. DWBA ANALYSIS AND DISCUSSION

As pointed out by the authors,[4] the observed violation of the "Barshay-Temmer" theorem could arise from one, or a combination, of the following sources: (1) isospin impurities in the incident channel (most likely the deuteron), (2) isospin impurities in the exit channel, (3) isospin mixing in an intermediate state, or (4) asymmetries introduced by the reaction mechanism.

Let us consider, first, that the source of the asymmetry arises from (3) above. In simplified terms the reaction could proceed in part via the excitation of a resonance in the compound $^6$Li system which could mix isospin through the overlapping of two broad states with different isospin. This mechanism has been proposed by Murakami[16] to explain the appearance of an asymmetry in our early data[8] and the apparent symmetry in the much lower-energy data of Nam, Osetinskii, and Sergeev.[5] A broad resonance has been found[17] in $^6$Be from a study of $^3$He-$^3$He elastic scattering. A study[14] of $d$-$\alpha$ elastic scattering reveals no similar resonance in $^6$Li up to an excitation energy of 25.1 MeV. However, a study of $^3$He + $^3$H elastic scattering shows evidence for a broad $l = 3$ resonance in $^6$Li at an excitation of about 29 MeV. The fact that we could not conclusively eliminate an intermediate-state resonance as the origin of the asymmetry in the 27.4-MeV (c.m.) data published previously[8] provided the impetus for studying the reaction at the several different energies reported here. Since the additional data at 21.4 and 16.6 MeV (c.m.) do exhibit pronounced asymmetries and not a resonance-like behavior, it is felt that we may eliminate this cause from further consideration.

Source (4) above can be examined in the following way. In its simplest terms, the reaction studied here can be considered to proceed by a direct

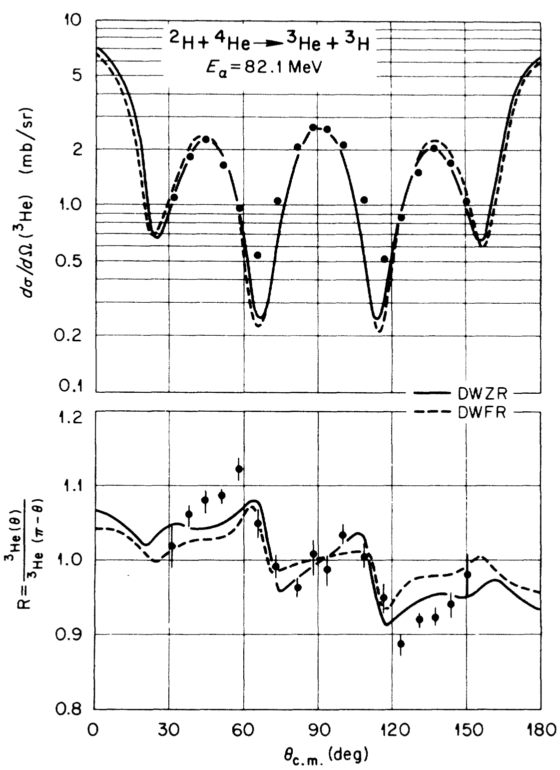


FIG. 3. In the upper half of the figure are shown the measured differential cross sections for $^3$He from the reaction $^4$He + $^2$H → $^3$He + $^3$H using an 82.1-MeV $\alpha$ beam. Relative errors are smaller than the size of the points. The angular dependence of the ratio of $^3$He to $^3$H yields is shown in the lower half of the figure. The solid curve is the prediction of a distorted-wave zero-range calculation and the dashed curve that of a distorted-wave finite-range calculation.

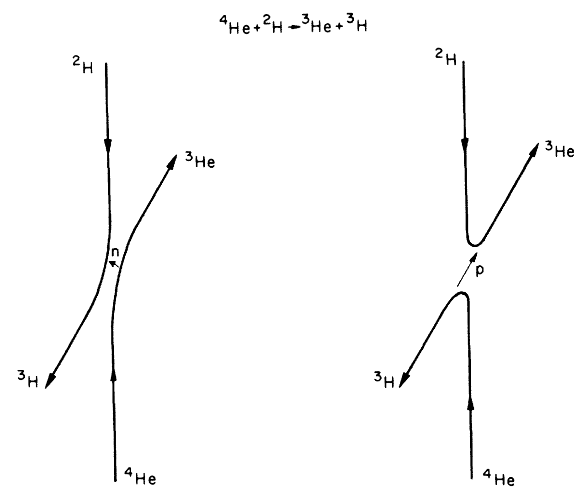


FIG. 4. Schematic representation of the single-nucleon, $l = 0$, transfer process assumed in the distorted-wave calculations.

single-nucleon-transfer reaction mechanism. It follows immediately that the observed cross section at any angle is thus the sum of the amplitudes from the single-neutron and single-proton transfers at complementary angles. A schematic representation of this is shown in Fig. 4. In the following paragraphs we describe the relevant calculations as made with the above assumption. The distorted-wave zero-range (DWZR) predictions presented were calculated with the code JULIE.[18] For the purpose of discussion, we shall consider first the distorting potentials for the incident channel, followed by those for the exit channel, and finally consider the bound-state wave functions.

The recent data of Hammond, Morales, and Cahill[14] on the elastic scattering of deuterons from $^4$He at incident energies of 27.1, 30.2, 35.0, and 39.6 MeV just about span the energy region required for the present analysis. The search code GENOA[19] was used to find a parametric set of optical potentials which would fit all four sets of data simultaneously. In addition to the usual three parameters describing the real well, the three parameters for the imaginary well, and the spin-orbit well depth, two additional parameters were introduced. These were the coefficients of energy-dependent terms for the real and imaginary well depths. In searching on the data it was found that fitting the small-angle (less than 90° c.m.) cross-sections well gave the best over-all fit, but there was some loss of phase at the backward angles. Good reproduction of the backward-angle data always resulted in a poor fit to the first observed minimum of the cross section in the 40° region. We selected the parameters from the best over-all fit for use in the entrance channel and these are shown in Table I. The spin-orbit well geometry was taken to be identical to that of the real well.

In an exactly analogous fashion, the data of Batten *et al.*[20] for the elastic scattering of $^3$He by $^3$H at 27.7 and 32.3 MeV was searched on. Although there were data only at two energies, this search also included an energy-dependent term in both the real and imaginary wells. The parameters derived from this search are also listed in Table I.

The bound-state form factors were calculated by

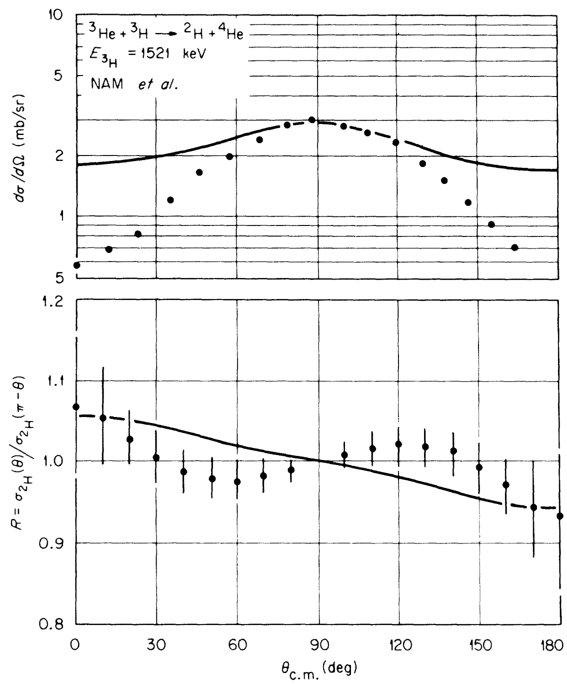


FIG. 5. In the upper half of the figure are shown the differential cross sections for the observed deuteron from the reaction $^3$He + $^3$H → $^2$H + $^4$He at $E_{3H}$ = 1521 keV from Ref. 5. The data points in the lower half of the figure result from a polynomial fit to the differential cross section and are related to the published $A(\theta)$ by $R(\theta)[1+A(\theta)]/[1-A(\theta)]$. The solid curve is the prediction of the distorted-wave zero-range calculation discussed in the text.

requiring the appropriate separation energy to be an eigenvalue of a Woods-Saxon well. These form factors were obtained by considering $^4$He as the core and removing either a proton or neutron to yield $^3$H or $^3$He, respectively. The separation energies differ by 763.8 keV and, of course, the form factor for the proton transfer contains the Coulomb term. To obtain the separation energy as an eigenvalue, the well depth is varied and is a function of the parameters $r_0$, $a$, and $r_C$ of the Woods-Saxon well. For the well parameters selected (1.20, 0.65, and 1.20 F, respectively), the well depths for the neutron and proton were the same to better than 100 keV out of ~75 MeV.

Rather than considering this reaction to proceed

TABLE I. Optical-model parameters.

| | $V$ (MeV) | $r_0$ (F) | $a$ (F) | $4W_D$ (MeV) | $W_0$ (MeV) | $r_g$ (F) | $b$ (F) | $V_{so}$ (MeV) | $r_C$ (F) |
|---|---|---|---|---|---|---|---|---|---|
| $d+{}^4$He | $83.9-0.2E$ | 1.050 | 0.620 | $0+0.28E$ | 0 | 2.56 | 0.650 | 8.0 | 1.30 |
| $^3$He + $^3$H | $160.0+1.0E$ | 1.25 | 0.575 | 0 | 20.0 | 1.82 | 0.20 | 0 | 1.40 |

via the above pickup process, calculations can be made for the inverse reaction assuming single-nucleon stripping. The bound-state form factors, and thus the calculated cross sections, are significantly different from the pickup process because of the large difference in the separation energies. The predicted angular distributions and asymmetries are, however, essentially identical when the same distorting potentials and Woods-Saxon parameters are used.

It is not our intention to give the impression that the above justifies the use of the simplifying assumptions made in this application of the distorted-wave (DW) theory. We realize that the use of the optical-model and Woods-Saxon approach to generate wave functions for such light nuclei may be suspect, particularly since wave functions for all of the particles exist in other forms. The aim here, however, is to show that the calculations were made in a self-consistent manner. The results of the DWZR predictions both for the differential cross sections and the asymmetries are shown as the solid curves in Figs. 1–3.

As can be seen, the fits to the observed differential cross section at the highest and lowest energies is quite satisfactory as is the shape of the predicted asymmetry. At the intermediate energy, however, the predictions fail to correctly reproduce the maxima at approximately 30° and are much too deep for the minima at 60°. In view of this rather poor fit it is not surprising that the calculated asymmetry does not reproduce the observed one at this energy. But it is worth noting that the general features of the asymmetry are at least qualitatively reproduced.

As mentioned in the Introduction, Nam, Osetinskii, and Sergeev[5] have studied the same reaction as reported here but in the inverse direction, i.e., $^3He + {}^3H \rightarrow {}^2H + {}^4He$, at five energies between 1044 and 1521 keV. These workers have analyzed their results by fitting a sixth-order Legendre-polynomial expansion to the observed deuteron angular distributions. From this analysis they obtain values for the asymmetry $A(\theta)$, but report that the angular distributions are consistent with 90° symmetry within the limits of experimental error. Their asymmetry is related to the convention we have chosen for $R(\theta)$ by

$$R(\theta) = [1 + A(\theta)]/[1 - A(\theta)] .$$

We have applied the single-nucleon-transfer calculations to their highest-energy data, 1521 keV, with the results shown in Fig. 5. The DWZR calculations predict a much slower angular dependence than that observed. It is not too surprising that the calculations are failing here, since the c.m. energy in the $^3He$-$^3H$ system is only 760 keV. The predicted asymmetry, however, has roughly the same magnitude as those reported at small angles, but deviates in magnitude and slope at backward angles.

The sensitivity of the calculations to the distorting potentials was investigated by individually varying the parameters by 10% and by observing the effect on the differential cross section and the fore-aft ratio. Aside from variations in predicted magnitudes for the angular distributions, the shapes of the calculated curves were surprisingly stable. There did appear to be more sensitivity to the exit channel than to the entrance channel. A spin-orbit potential of 2 MeV was tried in the $^3He$-$^3H$ channel with the effect of greatly increasing the depth of the minima at 20°. Since no real justification for the inclusion of this term could be made, it has not been included.

It is obvious that in the system treated here the interaction distances may not necessarily be small in comparison with the size of the deuteron and $\alpha$ particle. It is, therefore, important to consider the role finite-range effects might play in the reaction. A full distorted-wave finite-range calculation (DWFR) was made at each of the energies using the same parameters as above and a range[21] of 1.5 F. The absolute cross sections of the DWFR predictions are larger than those of the DWZR, and the results of these predictions have been normalized to the data at 90° c.m. and are shown as dashed lines in Figs. 1–3. The fits to the data are qualitatively the same for both calculations although the predicted asymmetry is generally less for the DWFR calculation than for the zero-range one.

Since the entrance and exit channels for the proton and neutron transfers are identical, the origin of the predicted asymmetry can be traced immediately to the difference in the bound-state form factors. As was pointed out above, these form factors have a slightly different radial dependence because of the difference in the proton and neutron separation energies. This difference in separation energy is, as is well known, a consequence of the Coulomb energy of $^3He$ and $^3H$. To demonstrate the point more forcefully, the separation energies for the two transfers may be artificially set equal, but the Coulomb term in the proton transfer retained. The asymmetry that is thus calculated has the same shape as the "true" case but its magnitude is reduced to about $\frac{1}{3}$ the original. It is obvious that if the calculations are made with both the separation energies and the Coulomb terms equal, there is no predicted asymmetry.

Finally, spectroscopic factors for the neutron and proton transfers may be deduced from a comparison of the observed and DWZR-predicted cross sections at the three energies. The values we obtain for $C^2S$ at 82.1, 64.3, and 49.9 MeV are 0.85, 0.84, and 1.00, respectively. These values are to be compared with an expected value of unity.

## V. CONCLUSIONS

The DW calculations based on a simple $l=0$ single-proton and single-neutron transfer demonstrate that the observed fore-aft asymmetry is a direct consequence of the respective proton and neutron separation energies from $^4$He. The differential cross sections are reproduced quite well for the highest and lowest energies studied, but the fit to the intermediate-energy data is rather poor. The origin of this anomaly is not clear at the present time.

It should be pointed out that at all the energies the calculated asymmetries have the correct shape but are generally less than the observed ones. This may in some way indicate that there is yet another source of isospin impurity involved either in the entrance or exit channels. However, before such a conclusion can be reached more complete calculations with more accurate wave functions for the participating particles will be required.

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