[3] G. R. Satchler, in *Proceedings of the Third International Symposium on Polarization Phenomena in Nuclear Reactions* (Univ. of Wisconsin Press, Madison, Wis., 1971), p. 167.

[4] N. Austern, *Direct Nuclear Reaction Theories* (Wiley, New York, 1970), 1st ed., p. 125.

[5] W. A. Kolasinski, J. Eenma, F. H. Schmidt, H. Sherif, and J. R. Tesmer, Phys. Rev. 180, 1006 (1969).

[6] J. R. Tesmer and F. H. Schmidt, Phys. Rev. Lett. 26, 857 (1971).

[7] R. de Swiniarski, A. D. Bacher, F. G. Resmini, G. R. Plattner, D. L. Hendrie, and J. Raynal, Phys. Rev. Lett. 28, 1139 (1972); R. de Swiniarski, H. E. Conzett, C. R. Lamontagne, B. Frois, and R. J. Slobodrian, Can. J. Phys. 51, 1293 (1973).

[8] J. S. Blair and H. Sherif, in *Proceedings of the Third International Symposium on Polarization Phenomena in Nuclear Reactions* (Univ. of Wisconsin Press, Madison, Wis., 1971), p. 692.

[9] J. Raynal, in *The Structure of Nuclei* (International Atomic Energy Agency, Vienna, Austria, 1972), p. 75.

[10] W. H. Tait and V. R. W. Edwards, Nucl. Phys. A203, 193 (1973).

[11] G. W. Greenlees, G. J. Pyle, and Y. C. Tang, Phys. Rev. Lett. 17, 33 (1966).

[12] G. W. Greenlees, G. J. Pyle, and Y. C. Tang, Phys. Rev. 171, 1115 (1968).

[13] The simple picture proposed here bears primarily upon the real central potential. The absorptive part is usually considered on a phenomenological basis. Since the imaginary spin-independent potential is probably determined mainly by the central *N-N* force, it is natural to assume a similar averaging effect for the corresponding βR value.

[14] The derivation of the Thomas form indicated in Ref. 12 is easily extended to nonspherical nuclei.

[15] B. J. Verhaar, "Polarization Effects in Inelastic Scattering", in Lecture Notes in Physics (Springer, Berlin, to be published).

[16] G. W. Greenlees, W. Makofske, and G. J. Pyle, Phys. Rev. C 1, 1145 (1970).

[17] D. L. Hendrie, Phys. Rev. Lett. 31, 478 (1973).

[18] F. Hinterberger, G. Mairle, U. Schmidt-Rohr, and G. J. Wagner, Nucl. Phys. A115, 570 (1968).

Difference between Polarization and Analyzing Power in the Reaction $^3\mathrm{H}(p,n)^3\mathrm{He}$

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We have examined the difference between polarization and analyzing power for the reaction $^3\mathrm{H}(p,n)^3\mathrm{He}$. We find that this difference is due to the presence of $^3P_2 \leftrightarrow {}^3F_2$ transitions which are enhanced in the vicinity of the lowest 2^- state of $^4\mathrm{He}$.

In a recent Letter, Haight *et al.* observed a surprisingly large and systematic difference between their analyzing power (A) data for the reaction $^3\mathrm{H}(p,n)^3\mathrm{He}$ using polarized protons and published polarization data (P) for $^3\mathrm{H}(p,n)^3\mathrm{He}$ for polarized neutrons in the energy range from 1.5 to 4 MeV. Their observation is of interest because the assumptions of charge symmetry [which implies $P = \overline{P}$, where $\overline{P}$ denotes the polarization for the reciprocal reaction $^3\mathrm{He}(n,p)^3\mathrm{H}$ with polarized protons] and time-reversal invariance (which implies $A = \overline{P}$) together require P and A to be equal for this reaction. An approximate equality between P and A is to be expected if all charge-dependent effects are small. In the present Letter, we show how the difference between P and A provides a strong constraint on a partial-wave analysis of the reaction $^3\mathrm{H}(p,n)^3\mathrm{He}$, and that a simple analysis of the difference observed in the energy range 1.5–4 MeV leads to the conclusion that f waves are important in the nucleon channels at these low energies. We discuss implications of this result for the structure of $^4\mathrm{He}$.

Subsequent measurements[2,3] of both P and A have revealed that these quantities are equal to within experimental uncertainties in the energy range 6–14 MeV. In addition, Brown and Rohrer[4] have further documented the difference between P and A at low energies by measuring angular distributions of A and comparing their measurements with corresponding ones of P by Smith and Thornton.[5] Associated-Legendre-polynomial coefficients were derived from a least-squares analysis of the angular-distribution data[4,5] using the expression

$$k^2 \frac{d\sigma}{d\Omega}\begin{bmatrix} P \\ A \end{bmatrix} = \sum_{L=1}^{L_{\max}} \begin{bmatrix} A_L(P) \\ A_L(A) \end{bmatrix} P_L{}^1(\cos\theta). \tag{1}$$

Nonnegligible coefficients were obtained for $L < 3$ and are shown in Fig. 1. Both P and A are dominated by the $P_2{}^1$ coefficient in the energy range from 1.5 to 3 MeV, a feature which was used by Barrett, Walecka, and Meyerhof[6] to establish the level ordering of the lowest negative-parity states of ^{4}He. It is also evident in Fig. 1 that the difference between P and A is dominated by the $P_2{}^1$ coefficient; it is this latter feature which provides new information on the structure of ^{4}He.

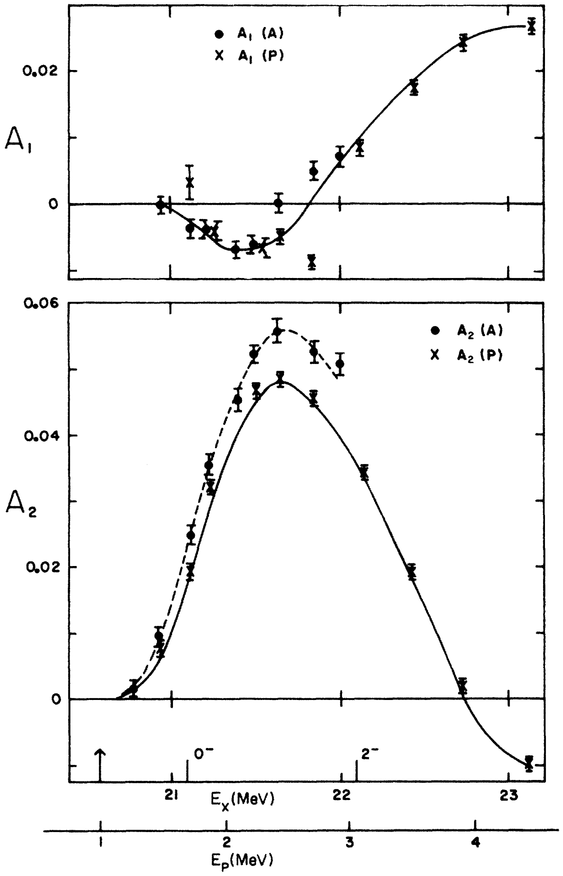

FIG. 1. Comparison of the coefficients $A_L(P)$ and $A_L(A)$ for $L = 1$ and 2. For A_2, polarization data-analysis results (Ref. 5) are connected by a solid curve; analyzing-power data-analysis results (Ref. 4) are connected by a dashed curve. These curves are intended as a guide to the eye. The arrow (lower left-hand corner) denotes the ^{3}H$(p,n)^3$He threshold. The positions of the 0^- and 2^- states of ^{4}He are taken from Ref. 8, but it should be noted that these states are broad enough to span the energy range of the figure.

The expansion of $A_L(P) - A_L(A)$ can be written as a sum of terms which have the form

$$C_L \operatorname{Im}[U_{tkt'k'}{}^{J'\pi'}(U_{sls'l'}{}^{J\pi} - U_{s'l'sl}{}^{J\pi})^*], \tag{2}$$

where $U_{sls'l'}{}^{J\pi}$ is a matrix element from the submatrix of the $J\pi$ partial wave collision matrix for the type of scattering being considered, and C_L is a coefficient whose value depends on the angular-momentum and parity quantum numbers of the matrix elements in the term. In the case of an elastic scattering submatrix, time-reversal invariance forces $U_{sls'l'}{}^{J\pi}$ and $U_{s'l'sl}{}^{J\pi}$ to be equal. In the case of a reaction submatrix for (p,n) reactions proceeding through self-conjugate compound nuclei, the additional constraint of charge symmetry is necessary in order to force $U_{sls'l'}{}^{J\pi} = U_{s'l'sl}{}^{J\pi}$. Since some charge dependence is expected, the equality of $U_{sls'l'}{}^{J\pi}$ and $U_{s'l'sl}{}^{J\pi}$ for such a reaction is only approximate and a comparison of P and A provides a measure of the differences, $U_{sls'l'}{}^{J\pi} - U_{s'l'sl}{}^{J\pi}$ These differences can occur in three varieties: channel-spin transition differences ($s \neq s', l = l'$), orbital-momentum transitions differences ($s = s'$, $l \neq l'$), and combined channel-spin–orbital transition differences ($s \neq s', l \neq l'$). The U-matrix elements that describe these transition differences are often small in magnitude and therefore difficult to isolate in a partial-wave analysis of cross-section and polarization (or analyzing power) measurements; consequently, the comparison of P and A is a potentially strong constraint on a partial-wave analysis of (p,n) reactions proceeding through self-conjugate compound nuclei.

The following U-matrix–element differences occur for ^{3}H$(p,n)^3$He when $l, l' \leqslant 3$: $U_{0111}{}^{1^-} - U_{1101}{}^{1^-}$, $U_{0212}{}^{2^+} - U_{1202}{}^{2^+}$, $U_{0313}{}^{3^-} - U_{1303}{}^{3^-}$ for channel-spin transitions; and $U_{1012}{}^{1^+} - U_{1210}{}^{1^+}$, $U_{1113}{}^{2^-} - U_{1311}{}^{2^-}$ for orbital-momentum transitions. Combined channel-spin–orbital transitions are not allowed for this reaction. Only the 1^- channel-spin transition has been considered previously.[7] Each of the above differences can occur in a given coefficient $A_L(P) - A_L(A)$ unless forbidden by angular-momentum coupling rules, or unless there are accidental cancelations in C_L. The number of terms with the form of Eq. (2) which occur in a given $A_L(P)-A_L(A)$ is large; however, those terms for which $|U_{tkt'k'}{}^{J'\pi'}|$ is appreciably different from zero[8] should be the dominant contributors, and they are relatively few in number when the reaction proceeds through a limited number of states of the compound system. The important U-matrix elements for $^3\mathrm{H}(p,n)^3\mathrm{He}$ and their maximum moduli in the energy range of interest[9] are $U_{0000}{}^{0+}$ (0.9), $U_{1111}{}^{0-}$ (1.0), $U_{1111}{}^{2-}$ (0.8), $U_{1111}{}^{1-}$ (0.4), and $U_{0101}{}^{1-}$ (0.3). If the expansions of $A_L(P)-A_L(A)$ are restricted to these U-matrix elements, then they are given by

$$A_1(P)-A_1(A)\approx \tfrac{3}{16}\,\mathrm{Im}[\sqrt{2}U_{0000}{}^{0+}(U_{0111}{}^{1-}-U_{1101}{}^{1-})^* + \tfrac{1}{2}\sqrt{2}\,Y(U_{1012}{}^{1+}-U_{1210}{}^{1+})^* + (\tfrac{3}{2})^{1/2}Z\,(U_{0212}{}^{2+}-U_{1202}{}^{2+})^*], \tag{3a}$$

$$A_2(P)-A_2(A)\approx \tfrac{3}{16}\,\mathrm{Im}[(\tfrac{50}{27})^{1/2}U_{0000}{}^{0+}(U_{0212}{}^{2+}-U_{1202}{}^{2+})^* + \tfrac{1}{2}\sqrt{2}Z\,(U_{0111}{}^{1-}-U_{1101}{}^{1-})^* + \tfrac{1}{2}(\tfrac{50}{27})^{1/2}Y(U_{1113}{}^{2-}-U_{1311}{}^{2-})^* + (\tfrac{4}{3})^{1/2}Z\,(U_{0313}{}^{3-}-U_{1303}{}^{3-})^*], \tag{3b}$$

$$A_3(P)-A_3(A)\approx \tfrac{3}{16}\,\mathrm{Im}[\tfrac{7}{9}\sqrt{3}U_{0000}{}^{0+}(U_{0313}{}^{3-}-U_{1303}{}^{3-})^* + (\tfrac{2}{3})^{1/2}Z\,(U_{0212}{}^{2+}-U_{1202}{}^{2+})^*], \tag{3c}$$

$$A_4(P)-A_4(A)\approx \tfrac{3}{16}\,\mathrm{Im}[\tfrac{1}{2}\sqrt{3}Z\,(U_{0313}{}^{3-}-U_{1303}{}^{3-})^*], \tag{3d}$$

where

$$Z=2U_{0101}{}^{1-}-U_{1111}{}^{1-}-U_{1111}{}^{2-}, \tag{4}$$

$$Y=2U_{111}{}^{1-}-U_{1111}{}^{0-}-U_{1111}{}^{2-}. \tag{5}$$

The sign $\approx$ in Eqs. (3a)–(3d) signifies that other terms with U-matrix elements of smaller moduli have been neglected.

The experimental data require $A_1(P)\approx A_1(A)$, $A_3(P)\approx A_3(A)\approx 0$, and $A_4(P)\approx A_4(A)\approx 0$. Unless these features of the coefficients are the result of cancelations[10] of the terms in Eqs. (3a), (3c), and (3d) over the entire energy range from 1.7 to 3 MeV, all of the U-matrix-element differences $U_{sls'l'}{}^{J\pi}-U_{s'l'sl}{}^{J\pi}$ that occur in these equations must be small. The only difference that survives in Eq. (3b) is $U_{1113}{}^{2-}-U_{1311}{}^{2-}$. Thus, in the absence of cancelations, the difference between P and A is due to the presence of $^3P_2 \rightarrow {}^3F_2$ transitions in the reaction $^3\mathrm{H}(p,n)^3\mathrm{He}$; to be more precise, it is the result of a difference between the $^3P_2\rightarrow{}^3F_2$ and the $^3F_2\rightarrow{}^3P_2$ transition amplitudes. These transitions take place in the resonant 2^- partial wave, and suggest that the 2^- state of $^4\mathrm{He}$ at 22.1 MeV excitation energy[11] ($E_p \approx 3.1$ MeV) has an appreciable f-wave partial width.

The present analysis of the difference between P and A provides fairly unambiguous evidence for the importance of f waves in the 2^- partial wave. In this regard, it is of some interest to note that observations[6] based on the behavior of $A_2(P)$ remain intact. The large values of $A_2(P)$ and $A_2(A)$, as well as their difference, are due to the 0^- and 2^- states of $^4\mathrm{He}$. The explanation of the difference between P and A given here is not likely to alter the previously established gross features of the structure of $^4\mathrm{He}$ between 20 and 30 MeV. It does, however, provide new information about the details of this structure which has a direct bearing on the analysis of other experiments and theoretical models. For example:

(1) The possible importance of f waves in the nucleon channels of the reactions $^2\mathrm{H}(d,p)^3\mathrm{H}$ and $^2\mathrm{H}(d,n)^3\mathrm{He}$ was noted some time ago,[12] and has continued to be a source of difficulty in their analysis.[13,14] Penetrability considerations, which would apply equally well to the reaction $^3\mathrm{H}(p,n)^3\mathrm{He}$, are the basis for arguments used to neglect $^3P_2\rightarrow{}^3F_2$ transitions[15] in the analysis of the above deuteron-induced reactions. The result of the present work indicates that the pentrability arguments are inadequate because they do not take into account the 2^- state at 22.1 MeV. The width of this state is about 5 MeV, which is broad enough to overlap the d-d threshold at 23.8 MeV.

(2) The shell-model interpretation of the negative-parity states of $^4\mathrm{He}$ is based on the $1\hbar\omega$ harmonic-oscillator configuration $(1s^3)(1p)$. Since it is not possible for a state from this configuration to have an f-wave partial width, the result of the present work indicates a need for the $3\hbar\omega$ configuration $(1s^3)(1f)$ in the description of the 2^- state. It might appear surprising that $3\hbar\omega$ configurations, which have zeroth-order excitation energies of about 50 MeV, would have much effect on states near 22 MeV. However, both the two- and three-nucleon systems require significant $2\hbar\omega$ admixtures to describe adequately the D-state components of their ground states. The 2^- state of $^4\mathrm{He}$ is above the thresholds for emission of trinucleon fragments, so the wave func-

tion for this state must behave asymptotically like the wave function for the relative motion of a nucleon and a *physical* trinucleon. An oscillator description of the trinucleon D state requires the $(1s^2)(1d)(1p)$ configuration in the wave function, and this configuration leads to an admixture of the $(1s^3)(1f)$ configuration when spurious c.m. excitations are eliminated from the $3\hbar\omega$ configurations. If the above picture is qualitatively correct, the D-state amplitudes of composite fragments (~25% in magnitude) play an important role in the description of the ${}^3P_2 \to {}^3F_2$ transitions.

We conclude with suggestions for measurements which would be useful in a more complete analysis of the difference between P and A in the reaction ${}^3\mathrm{H}(p,n){}^3\mathrm{He}$. First, it would be desirable to have measurements of P and A carried out under as nearly identical circumstances as possible in the energy range from 1.2 to 6 MeV. Second, excitation-function measurements of P and A near $\theta_{\mathrm{c.m.}} = 90^\circ$, where the contribution from the $P_2{}^1$ coefficient is minimal, would be particularly useful for the purpose of determining the extent to which the difference between P and A is confined to the $P_2{}^1$ coefficient.

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[1] R. C. Haight, J. J. Jarmer, J. E. Simmons, J. C. Martin, and T. R. Donoghue, Phys. Rev. Lett. 28, 1587 (1972).

[2] J. J. Jarmer, R. C. Haight, J. E. Simmons, J. C. Martin, and T. R. Donoghue, to be published.

[3] J. J. Jarmer, R. C. Haight, and J. E. Simmons, unpublished.

[4] L. Brown and U. Rohrer, to be published.

[5] J. R. Smith and S. T. Thornton, Nucl. Phys. A186, 161 (1972).

[6] B. R. Barrett, J. D. Walecka, and W. E. Meyerhof, Phys. Lett. 22, 450 (1966).

[7] C. Werntz and W. E. Meyerhof, Nucl. Phys. A121, 38 (1968).

[8] Unitarity requires $0 \leq |U_{tkt'k'}{}^{J'\pi'}| \leq 1$.

[9] The moduli of the U-matrix elements are taken from I. Ya. Barit and V. A. Sergeev, Yad. Fiz. 12, 1230 (1971) [Sov. J. Nucl. Phys. 13, 708 (1971)].

[10] The possibility of systematic cancelations cannot be easily dismissed because the U-matrix elements from existing analyses do not exhibit dramatic variations with energy over the region of interest. On the other hand, they do not vary so slowly in energy as to make cancelations likely. The following elimination procedure was used in this analysis. If Eqs. (3c), (3d) are set equal to zero, then $U_{0313}{}^{3-} - U_{1303}{}^{3-} = 0$, and either $Z \approx 0$ or $U_{0212}{}^{2+} - U_{1202}{}^{2+} = 0$. The possibility that $Z \approx 0$ throughout the energy region cannot be ruled out, but it seems unlikely since the U-matrix elements in Z are resonant at different energies. The first term in the brackets of Eq. (3a), $U_{0000}{}^{0+}(U_{0111}{}^{1-} - U_{1101}{}^{1-})^*$, could be ineffective even with a nonzero second factor if the imaginary part of the product happened to be small over the energy region; this also seems unlikely. The difference, $U_{1012}{}^{1+} - U_{1210}{}^{1+}$, can be taken to be zero without affecting the conclusions.

[11] S. Fiarman and W. E. Meyerhof, Nucl. Phys. A206, 1 (1973).

[12] F. M. Beiduk, J. R. Pruett, and E. J. Konopinski, Phys. Rev. 77, 622 (1950).

[13] L. J. B. Goldfarb and H. E. Reed, Phys. Lett. 27B, 140 (1968), and references therein.

[14] K. Jeltsch, A. Janett, P. Huber, and H. R. Striebel, Helv. Phys. Acta 43, 279 (1970).

[15] All ${}^3P \to {}^3F$ transitions in the reactions ${}^2\mathrm{H}(d,p){}^3\mathrm{H}$, ${}^2\mathrm{H}(d,n){}^3\mathrm{He}$, and ${}^3\mathrm{H}(p,n){}^3\mathrm{He}$ are restricted to the 2^- partial wave, and therefore related by unitarity.