Analyzing Power at 45° from 1.5 to 12 MeV for the Reaction T$(p,n)^3$He†

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The analyzing power A of the reaction T$(p,n)^3$He has been measured at 45° c.m. from 1.5 to 12 MeV with a polarized proton beam. A comparison with existing data for the neutron polarization P shows that P and A have similar excitation functions at this angle, but that the magnitude of P is generally less than that of A. While the R-matrix formalism does not require exact equality between P and A, we do not have at present a successful explanation of the observed differences.

The polarization P of a particle X elastically scattered by another particle Y is well known[1] to be equal to the analyzing power A for elastic scattering of a polarized beam of X by Y. This equality follows from time-reversal invariance. Although the reaction T$(p,n)^3$He is not elastic scattering, the initial and final states differ to a good approximation only by a reflection in isospin space. That is, if all protons are changed to neutrons and vice versa, the initial state is changed to the final state. Thus if charge-dependent and the concomitant Q-value effects are ignored, one might expect the outgoing neutron polarization P, with the incident beam unpolarized, to be equal to the analyzing power A when the reaction is initiated with a polarized beam.

The motivation for the present experiment was threefold. First, it is interesting to explore the deviation from approximate symmetries which act as guides for future experiments. In support of the hypothesis that P and A might be similar, calculations[2] based on the parameters of a charge-independent R-matrix analysis[3] show that P and A are nearly equal in this energy range. The comparison of P and A therefore sheds light on the assumption of charge independence in general and its use in particular in this type of R-matrix analysis. Second, more data on the $A=4$ system are useful in support of the R-matrix analysis now underway at this laboratory.[4] The fact that the analyzing powers could be measured more precisely than neutron polarizations will lead to an improvement in our knowledge of the $A=4$ system. Third, if it can be established that $P=A$, then a measurement of A which can be done easily to good precision implies accurate values of P. The latter are useful when the reaction T$(p,n)^3$He is used as a source of polarized neutrons.

The analyzing power has been measured in this work from 1.5 to 12 MeV at 45° c.m. The large body of polarization data existent at this angle then allows a comparison of P and A.

The experimental method in outline was as follows. A beam of polarized protons produced by the Los Alamos Scientific Laboratory Lamb-shift[5] polarized ion source was accelerated by a model FN tandem Van de Graaff accelerator. The dc polarized proton beam was directed onto a 3-cm-long target containing gaseous tritium at 1.07 or 3.45 atm absolute. The lower pressure was used for proton energies <3 MeV. Neutrons produced from the reaction T$(p,n)^3$He were detected by a cylindrical (4.44 cm by 4.44 cm) NE-213 scintillator. The scintillator was positioned 85.0 cm from the target. γ rays were electronically separated from neutrons by pulse-shape discrimination. Background neutrons were measured by taking target-empty runs at selected energies. Neutron backgrounds were small, a typical ratio of background to signal being 0.002 at 2.908 MeV incident proton energy. The asymmetry was measured by reversing the polarization of the beam at the ion source. Beam polarization was measured by an atomic-beam technique[6] to ± 0.015 and was typically 0.90. Two cycles of $+--+$ beam polarization were taken at each point where $+$ $(-)$ denotes proton spin up (down). Each measurement in a cycle was taken for the same integrated beam current. Four repeat measurements between 2 and 10 MeV showed that values were reproducible within the statistical error. To obtain an estimate of systematic error,

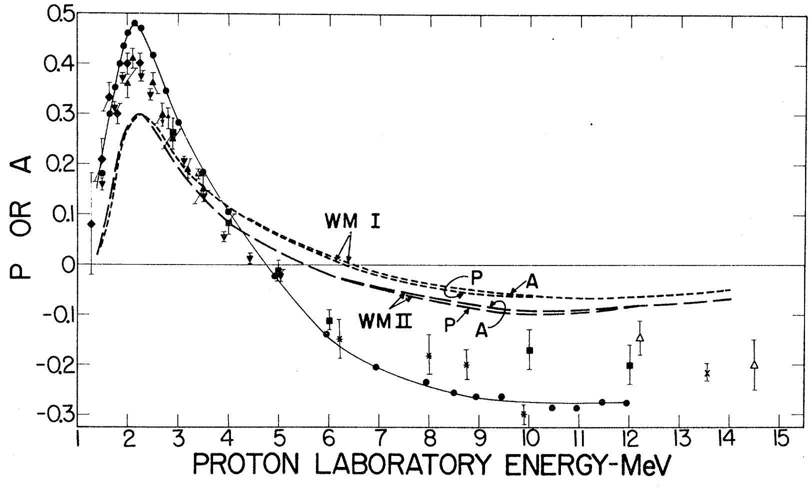

FIG. 1. Analyzing power at 45° c.m. and polarization near 45° c.m. for $T(p,n)^3He$ versus proton lab energy. Analyzing power data (closed circles) are connected by the solid curve (to guide the eye). Polarization data: diamonds, Ref. 8, 31.6° lab; inverted closed triangles, Ref. 9, 45° c.m.; upright closed triangles, Ref. 10, 33° lab; squares, Ref. 11, 45° c.m.; asteriks, Ref. 12, 40° lab; open triangles, Ref. 13, 47° c.m.; crosses, Ref. 14, 30° lab.

measurements were taken at 0°, where A should be identically zero, for proton energies of 13.55 and 6.00 MeV. The results were 0.0023 ± 0.0026 and -0.0048 ± 0.0023. For this and other reasons, the systematic errors in A due to current integration and neutron detection are believed to be less than 0.005. Errors in the measurement of the proton polarization have been discussed previously.[6] At low energies, the depolarization by electron capture and loss increases to the order of 2% at 2 MeV and depends on the (unmeasured) residual gas pressure in the tandem terminal.[7] On the other hand, polarization enhancement by the "beam scraping" effect may be larger at these low energies than as discussed in Ref. 6. No correction has been made for these effects which we regard as increasing the uncertainty in proton polarization at low energies to about 2.5% at 2 MeV.

The results for the analyzing power of the reaction $T(p,n)^3He$ (protons polarized) are given in Fig. 1 as the closed circles connected by the solid line which is sketched as a guide to the eye. The statistical errors in A are smaller than the size of the circles and are typically ± 0.003. Uncertainties in the proton polarization are not included here. Also shown in the figure are measurements[8-14] of neutron polarization (proton beam unpolarized) made near 45° c.m. The associated Legendre polynomial coefficients of Ref. 9 were used to interpolate their values to 45° c.m. All the other values are data points.

The long-dashed lines for P and A were calculated[2] from the R-matrix parameters of solution II of Werntz and Meyerhof[3] (WM). Below 6.5 MeV, P and A are equal to within 0.004. Calculations given by the short-dashed lines in Fig. 1 and based on solution I of WM yield essentially the same relationship between P and A. They also yield values of P and A within 0.02 of those from solution II below 3.0 MeV. Above 4 MeV, the solution-II values describe these data somewhat better than those of solution I.

The comparison in Fig. 1 of the P and A data illustrates their very similar features. The experimental maxima at about 2.2 MeV in both P and A confirm the resonant structure of the reaction mechanism noted previously.[3] The fact that the maxima occur at the same energy is a qualitatively different effect from the final-state interaction observed in $D(d,n)^3He$ and $D(d,p)T$ nucleon polarization measurements[15] where the nucleon polarization is the same at the same relative kinetic energies in the outgoing system, that is, at energies differing by about 764 keV in the ^4He system. Second, A differs experimentally from P by only about 17% relative in the range 1.7 to 4 MeV. Terms that make $P \neq A$ are therefore relatively small. Third, the R-matrix calculations with the parameters of WM, with either solution I or solution II, account well for the location of the maxima and qualitatively for the complete excitation function.

On the other hand, the present experimental results indicate that $P \neq A$ in the region 1.7 to 4 MeV where many polarization data exist. Here

A is higher than P by about 17% relative which is significantly larger than the quoted errors. It is conceivable that this difference relates to the existence of unknown systematic errors. With respect to the neutron polarization data, this possibility seems reduced because of the consistency of several different experiments. The magnitude of our own systematic errors as estimated above is much smaller than the observed difference.

In the 7–12-MeV range, the few existing polarization data barely suggest an inequality of P and A. This latter conclusion is weak, however, so that the following discussion will be limited to the 1.7–4-MeV interval.

Both the near equality of P and A and their apparent difference may be understood qualitatively if the observables are written in terms of the collision matrix elements, $U_{s'l'sl}$. The conventions and much of the notation of WM will be followed here. The restrictions of WM that $l \leq 2$, $J \leq 2$, and $s \neq 1$ if $l = 2$ will also be taken. It then follows that the analyzing power times the unpolarized differential cross section may be expanded in terms of associated Legendre polynomials,

$$A(\theta)k^2 \frac{d\sigma}{d\Omega}(\theta) = \sum_{L=1}^{3} A_L(A) P_L{}^1(\cos\theta), \qquad (1)$$

where

$$A_1(A) = \tfrac{1}{16}\,\mathrm{Im}[5U_{1010}{}^1U_{1111}{}^{2*} - 3U_{1010}{}^1U_{1111}{}^{1*} - 2U_{1010}{}^1U_{1111}{}^{0*} - 3\sqrt{2}\,U_{1010}{}^1U_{1101}{}^{1*} - 3\sqrt{2}\,U_{0000}{}^0U_{0111}{}^{1*} + 3\sqrt{2}\,U_{0202}{}^2U_{0111}{}^{1*}], \qquad (2)$$

$$A_2(A) = \tfrac{1}{16}\,\mathrm{Im}[3U_{1111}{}^1U_{1111}{}^{2*} + 2U_{1111}{}^0U_{1111}{}^{2*} - \tfrac{3}{2}\sqrt{2}\,U_{1111}{}^2U_{1101}{}^{1*} - \tfrac{6}{2}\sqrt{2}\,U_{0101}{}^1U_{0111}{}^{1*} - \tfrac{3}{2}\sqrt{2}\,U_{1111}{}^1U_{1101}{}^{1*}], \qquad (3)$$

$$A_3(A) = \tfrac{1}{16}\,\mathrm{Im}[-3\sqrt{2}\,U_{0202}{}^2U_{0111}{}^{1*}], \qquad (4)$$

and k is the magnitude of the center-of-mass wave vector in the initial channel. The expressions for the coefficients $A_L(P)$ describing $P(\theta)k^2 \times d\sigma(\theta)/d\Omega$ are obtained by interchanging the subscripts sl and $s'l'$ in Eqs. (2)–(4).[16] Thus, under the WM restrictions on s, l, and J, A is different from P only if $U_{1101}{}^1 \neq U_{0111}{}^1$.

In the parametrizations of WM, the $T = 1, 1^-$ states which give singlet-triplet mixing are at equivalent proton energies of about 7.5 and 10.9 MeV or well above the 1.7–4-MeV interval. They contribute little at the lower energies where the polarization and analyzing power are dominated by the second term in Eq. (3), namely, by the interference of the 0^- and 2^-, $T = 0$ states[17]; hence these parameters give $P \cong A$ here. Since the low-lying 0^- and 2^- states are described identically in WM I and WM II, the calculations give almost the same values for the two parameter sets in this energy region.

A modification of the WM parameters might account for the apparent difference between P and A. If the restrictions on s, l, and J are retained, then the magnitudes of $U_{0111}{}^1$ and $U_{1101}{}^1$ must be increased and their differences magnified. For example, to maximize the singlet-triplet mixing in the 1^- states, one could put the mixing parameter x equal to -1 instead of -0.3 or -3.3 as in WM. Werntz has suggested this possibility to describe the experimentally determined $A_1(P)$ coefficient better.[18] The result is to increase the magnitudes of $U_{0111}{}^1$ and $U_{1101}{}^1$ each by a factor of about 2 which is entirely inadequate to account for the apparent difference between P and A between 1.7 and 4 MeV. Two other ways to increase the singlet-triplet mixing in this energy region might be to move the $T = 1, 1^-$ states down in energy or to increase their widths. These two possibilities seem unacceptable, however: The $T = 1, 1^-$ states were chosen by WM to give a good description of p-^{3}He elastic scattering, which probably would not be described well with a large change in the $T = 1$ parameters of WM. At present, therefore, we do not have an explanation of the observed difference.

In conclusion, the calculated differences between P and A, which are small even near the position of the $T = 1, 1^-$ states, indicate that rather drastic modifications of the charge-independent parameters of WM will be necessary if the apparent 17% difference is to be reproduced from 1.7 to 4.0 MeV. If the modifications then fail to account for the large body of $A = 4$ data, the final unpleasant alternative is to abandon the assumption that the R matrix is charge independent.

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Resonance in $^{12}C + ^{16}O$ Scattering at $E_{c.m.} \approx 19.7$ MeV*

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A strong resonancelike structure (~ 400 keV wide) has been observed in elastic $^{16}O + ^{12}C$ scattering. Inelastic scattering excitation functions with ^{16}O in the unresolved $0^+, 3^-$ states at 6.1 MeV show structure correlated with the elastic channel. An analysis of the angular distribution measured on the resonance indicates a spin $I = 14$.

The observation[1,2] of possible "molecular states" in the $^{12}C + ^{12}C$ and $^{12}C + ^{16}O$ systems at energies close to the Coulomb barrier has led to much interest in this phenomenon. Narrow structures observed in the excitation functions at higher energies were found to be consistent with statistical fluctuations.[3,4] More recently, however, there has been increasing evidence[5] for the existence of structure of nonstatistical origin in addition to the fluctuation phenomena. In a study of $^{12}C + ^{16}O$ elastic scattering we observe a strong anomaly which, as discussed below, is indicative of a high-spin ($I = 14$) resonance in the ^{28}Si compound system. A preliminary report of this anomaly has already been given elsewhere.[6] Recently, an investigation of this anomaly has also been undertaken at Yale.[7]

Elastic-scattering excitation functions for the $^{12}C + ^{16}O$ system (Fig. 1) were measured in the energy range $E_{lab} = 20-60$ MeV with targets whose thicknesses were chosen to match the 250-keV energy steps. The forward-angle data have been omitted from Fig. 1 since they show much less structure. The associated-particle method was used with an array of large-area detectors, and the back-angle data (taken at 140°, 150°, and 160° c.m.) were obtained with detector telescopes in which the recoil ^{12}C ions were recorded.

The data in Fig. 1 exhibit strong rapid fluctuations superimposed on a broad gross structure (~ 2 MeV wide). A statistical analysis (with a running average cross section taken over a 1.3-MeV subinterval) yields a coherence width of approximately 110 keV in good agreement with the results of Halbert, Durham, and Van der Woude[4] and indicates no significant angular cross correlations.

However, at ~ 19.7 MeV a prominent structure[8]