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Proton and neutron polarization differences in the reactions $^3H(\vec{p},p)^3H$ and $^3He(\vec{n},n)^3He$†

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The reactions $^3H(\vec{p},p)^3H$ and $^3He(\vec{n},n)^3He$ are analyzed within the framework of the dynamical R-matrix methodology. When compared at equal incident energies, measurements indicate that forward angle $^3H(\vec{p},p)^3H$ polarization values are slightly in excess of $^3He(\vec{n},n)^3He$ values. The model predicts the proton polarization has a slightly larger magnitude at forward angles than the neutron polarization, although their shapes and magnitudes are in qualitative agreement with experiment. Lisowski's phase shift analysis suggests the existence of a narrow resonance near $E_x = 37$ MeV. The model predicts several resonances in the vicinity of this tentative level.

NUCLEAR REACTIONS Calculated $P(\theta)$ for $^3H(\vec{p},p)$ and $^3He(\vec{n},n)$ at 8.0, 12.0, and 17.1 MeV.

NUCLEAR STRUCTURE The R-matrix model predicts $J^\pi=1^+$, 2^+, 3^+, and 4^+ states near the position of the tentative narrow resonance of Lisowski *et al.*

I. INTRODUCTION

As evidenced by a recent compilation,[1] the ^4He system has been the subject of extensive experimental and theoretical investigations. As part of this investigation, measurements have recently been performed to determine angular distributions of the polarization produced in $^3H(\vec{p},p)^3H$ and $^3He(\vec{n},n)^3He$ elastic scattering.[2,3] The $^3H(\vec{p},p)^3H$ polarization data[2] ($7 < E_p < 15$ MeV), when compared to the $^3He(\vec{n},n)^3He$ data[4,5] at equal excitation energies, are found to exhibit a large difference. Because of this difference, the neutron polarization data were recently remeasured by Lisowski *et al.*,[3] and no substantial difference was found.

Since the nuclear interaction is believed to be independent of the charge of the nucleon, except for restrictions arising from the Pauli principle, light nuclei such as ^3H and ^3He are not expected to show a polarization difference as sizable as those noted by Hardekopf *et al.*[2] This difference is also significant because it could imply a breaking of exact charge symmetry by the Coulomb interaction and hence provides a mechanism for investigating charge symmetry breaking terms in the nuclear interaction.[6] In view of the significance of this difference and because of conflicting experimental results, we have decided to analyze the difference in $^3H(\vec{p},p)^3H$ and $^3He(\vec{n},n)^3He$ polarization.

An analysis of these reactions is also warranted because the recent polarization measurements[2,3] permit a more detailed evaluation of $^3H(p,p)^3H$ and $^3He(n,n)^3He$ phase shifts. The phase shift analysis of Lisowski *et al.* suggests the possibility of some narrow and hitherto unknown level (or levels) near 37 MeV in ^4He. Although the experimental evidence is not definitive, our model does predict several possible candidates for this level.

II. THEORY AND FORMALISM

The model for the ^4He nucleus used in this analysis treats the structure and reaction aspects on an equal footing.[7,8] This model is constructed within the framework of the dynamical R-matrix methodology.[9] The internal states are expanded on a basis of properly symmetrized translationally invariant harmonic oscillator eigenstates including all states up to $4\hbar\omega$ of oscillator excitation. All three two-body breakup channels, namely $p+{}^3H$, $n+{}^3He$, and $d+{}^2H$, are explicitly included.

Specific formulas for the positions and widths of R-matrix resonances are available in the literature.[10,11] In particular, the resonance energy E_R^μ corresponding to the level E_μ may be defined as the solution to the equation

$$E_R^\mu = \mathrm{Re}[E_\mu - \xi_\mu(E_R^\mu)] \,. \tag{1}$$

The total width of the resonances is then obtained from the equation

$$\Gamma_R^\mu = -2\mathrm{Im}[E_\mu - \xi_\mu(E_R^\mu)] \,, \tag{2}$$

where ξ_μ is itself defined in terms of known R-matrix energies and reduced widths E_μ, $\gamma_{\mu c}$, and standard Coulomb radial functions.[10,11] The partial width $\Gamma_R^{\mu c}$ is then obtained from the relation

$$\Gamma_R^{\mu c} = 2\,|\alpha_{\mu c}(E_R^\mu)|^2 P_c\,(E_R^\mu) \,, \tag{3}$$

where P_c is the penetration in channel c and the quantity $\alpha_{\mu c}$ is defined in Ref. 11.

Within our model of the ^4He system, the total width is given by

$$\Gamma_R^{\mu}=\sum_c \Gamma_R^{\mu c}, \tag{4}$$

where the label c runs over all $p+{}^3\mathrm{H}$, $n+{}^3\mathrm{He}$, and $d+{}^2\mathrm{H}$ channels in our $4\hbar\omega$ model space. The sum defined in Eq. (4) may be rewritten in terms of the partial decay widths into the various channels

$$\Gamma_R^{\mu}={}^p\Gamma_R^{\mu}+{}^n\Gamma_R^{\mu}+{}^d\Gamma_R^{\mu}, \tag{5}$$

where the labels p, n, and d refer to the various binary breakup channels. It should be noted that our definition of the level width does not include contributions from the three- and four-body breakup channels.

This R-matrix method provides a good description of both structure and reaction aspects of the ^{4}He system.[7,8] These techniques also provide a good description of the difference between the polarization and analyzing power in the $^3\mathrm{H}(p,n)^3\mathrm{He}$ reaction for $E_p < 4$ MeV.[12] Similar models have encountered equal success in describing the ^{4}H and ^{4}Li systems.[13]

III. CHOICE OF INTERACTION

In Ref. 8, an effective interaction for oscillator basis states was determined for the two, three, and four nucleon systems. This interaction was determined from the Sussex matrix elements[14] and is of the form

$$V^{\mathrm{eff}}=C\,V^{\mathrm{Sussex}}, \tag{6}$$

where C is a strength parameter of order unity. The parameter C and the oscillator size parameter b were varied independently. Good fits to the two, three, and four nucleon ground state properties[8] were obtained for $C=1.168$ and $b=1.60$ fm. Within our model space $4\hbar\omega$, this effective interaction also predicts a 4% D-state probability in the deuteron ground state and yields a ^{3}H-^{3}He Coulomb energy difference in agreement with experiment. The changes from the original Sussex matrix elements implied by our choice of C are typically of the same order of magnitude as the expected uncertainties in the matrix elements themselves.

IV. RESULTS AND DISCUSSION

The most recent data for $^3\mathrm{H}(\vec{p},p)^3\mathrm{H}$ polarization[2] and $^3\mathrm{He}(\vec{n},n)^3\mathrm{He}$ polarization[3] are found to be nearly equal, when comparisons are made at equal excitation energies in the compound system. This data has been included in parametrizations of proton[2] and neutron[3] complex phase shifts, and it is important to note that polarization functions calculated from these phase shifts, in an energy shifted manner, do not give identical results. The phase shift solutions of Lisowski *et al.* permit the formulation of three observations concerning proton and neutron polarization:

(1) There is some evidence that the $^3\mathrm{He}(\vec{n},n)^3\mathrm{He}$ data has a slightly larger polarization at forward angles than the $^3\mathrm{H}(\vec{p},p)^3\mathrm{H}$ data when compared at equal incident energies.

(2) Polarization differences of 0.03 at forward angles and 0.05 at backward angles are predicted.

(3) The zero crossing of the polarization (around 100° c.m.) occurs at an angle that is 3° less for $n+{}^3\mathrm{He}$ than for $p+{}^3\mathrm{H}$.

In order to investigate the validity of these contentions polarization functions are calculated for the $^3\mathrm{H}(\vec{p},p)^3\mathrm{H}$ and $^3\mathrm{He}(\vec{n},n)^3\mathrm{He}$ reactions, at equal excitation energies, for bombarding energies of 8.0, 12.0, and 17.1 MeV. The model results for these energies are very similar in both magnitude and shape when compared with data.[2,3] The model is in qualitative agreement with experiment even though the proton polarization is calculated to be slightly larger than neutron values. A possible explanation for the difference is the physical separation of the $p+{}^3\mathrm{H}$ and $n+{}^3\mathrm{He}$ channels by 763 keV. At equal excitation energies, the proton will be 763 keV closer to the low lying resonances in the ^{4}He system.[1] This would facilitate decay into these states, and, hence, enhance the proton polarization. The model does, however, predict polarization differences of 0.03 at forward angles and 0.05 at backward angles, which is in agreement with Lisowski's prediction. Our model also agrees with experiment in that the zero crossing of the polarization is near 100° c.m. and occurs at an angle that is 3° less for $n+{}^3\mathrm{He}$ than for $p+{}^3\mathrm{H}$.

The $n+{}^3\mathrm{He}$ phase shift analysis,[3] which predicted the qualitative features of the neutron polarization data, also suggests a narrow resonance near 37 MeV in ^{4}He. The existence of this state (or states) is suggested by apparent structure in the δ_{21}^2 and δ_{21}^3 phase shifts. Although the evidence is suggestive, additional $n+{}^3\mathrm{He}$ measurements between 17 and 24 MeV are needed to clarify the situation.

Our model predicts several levels in the vicinity of Lisowski's tentative state. These resonances and their widths are summarized in Table I. It should be noted that the positions of these levels are shifted several MeV above Lisowski's proposed experimental position.[3] These shifts are not unexpected and are very similar to those observed in the comparison of model results[8] with known experimental levels.[1]

Two of the predicted levels, 2^+ and 3^+, are suggested by structure in the $n+{}^3\mathrm{He}$ phase shifts. The 2^+ level is predicted to have a width of 960 keV while the 3^+ level is more narrow with a calculat-

TABLE I. Model resonances in the vicinity of the tentative experimental level near 37 MeV in ^{4}He.

J^π	E_R^μ (MeV)	$^p\Gamma_R^\mu$ (MeV)	$^n\Gamma_R^\mu$ (MeV)	$^d\Gamma_R^\mu$ (MeV)	Γ_R^μ (MeV)
1^+	41.84	0.08	0.08	0.07	0.23
2^+	43.11	0.25	0.25	0.46	0.96
3^+	41.98	0.01	0.01	0.06	0.08
4^+	42.37	0.07	0.07	3.85	3.99

ed width of 80 keV. A narrow 1^+ state, $\Gamma = 230$ keV, is also predicted, but there is no obvious resonance structure in the δ_{01}^1 and δ_{21}^1 phase shifts.[3] Finally, a 4^+ level with a width of 4 MeV is predicted by our model. This level has no phase shift counterpart because Lisowski's analysis only included partial waves for $L \leq 2$.

V. CONCLUSIONS

The results of this analysis support the contentions of the phase shift analysis of Lisowski *et al.* Proton and neutron polarization values, when compared at equal excitation energies, are found to be nearly equal. The R-matrix model predicts several states which may correspond to the narrow resonance near 37 MeV in the ^{4}He system. Before any definite spin assignments are attempted, more detailed neutron scattering measurements between 17 and 24 MeV are needed.

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