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To cite this version:

HAL Id: jpa-00230917
https://hal.archives-ouvertes.fr/jpa-00230917
Submitted on 1 Jan 1990

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D-STATE PARAMETER DETERMINATIONS FOR $^3\text{He}$ AND $^4\text{He}$


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Abstract - Determinations of the asymptotic D/S-state ratio for $^3\text{He}$ ($\eta$($^3\text{He}$)) using the ($d$, $^3\text{He}$) reaction and $D_2(4\text{He})$ using the ($d$,$\alpha$) reaction are being conducted. An attempt is made to extract D-state information using exact finite-range DWBA calculations with few free parameters. The sensitivity of calculations to factors such as optical model parameters, overlap function and choice of transition is examined. Cases discussed are the $(d,\alpha)$ reaction at $E_d=16$ MeV and $(d,\alpha)$ reaction at $E_d=22$ MeV.

1 - INTRODUCTION

Our work concentrates on the extraction of parameters, (e.g., $\eta$ and $D_2$) dependent on the D state of $^3\text{He}$ and $^4\text{He}$ using polarized ($d$, $^3\text{He}$) and polarized ($d$, $\alpha$) transfer reactions. Finite-range DWBA calculations have shown that the tensor analyzing powers $A_{xx}(\theta)$ and $A_{yy}(\theta)$ are sensitive to small $s=3/2$, $\ell=2$ components of the $d+p$ cluster in $^5\text{He}$ and $s=2$, $\ell=2$ components of the $d+d$ cluster in $^4\text{He}$.

Improved determinations of $\eta$($^3\text{He}$) are timely since recent experimental results (2) based on analytic-extrapolation methods and radiative-capture experiments yield $\eta(t)/\eta(3\text{He}) = 1.46 \pm 0.24$ while theoretical calculations for $^3\text{H}$ and $^3\text{He}$ assuming charge-symmetric nucleon-nucleon forces (3), predict $\eta(t)/\eta(3\text{He}) = 1.07 \pm 0.03$. Unambiguous determinations of parameters such as $\eta$ for $^3\text{He}$ are considerably more difficult than for $^3\text{H}$, since sub-Coulomb reactions have much lower yields and the analysis of analyzing-power measurements for higher-energy ($d$, $^3\text{He}$) reactions is sensitive to the choice of optical model potential (OMP) parameters.

Experimental determinations of $D_2$ for $^4\text{He}$ based on radiative capture and transfer reactions have resulted in a wide variety of values ($-0.31 \text{fm}^2 < D_2 < -0.08 \text{fm}^2$). Analyses of $^2\text{H}$ polarized ($d$, $\gamma$)($^4\text{He}$) reactions have been hampered by the complexity of the reaction mechanism, while previous ($d$, $\alpha$) studies have involved uncertainties in the mixture of contributing L-transfer values. The most reliable value extracted to date, $D_2 = -0.19 \pm 0.04 \text{fm}^2$, is based on a case of appreciable L mixing (4).

2 - EXPERIMENTAL METHODS

Measurements of the $^{32}\text{S}$ polarized ($d$, $^3\text{He}$)$^{31}\text{P}$ reaction at $E_d=16$ MeV were made with a vector and tensor polarized deuteron beam from the Lamb-shift polarized ion source at the Triangle Universities Nuclear Laboratory. Angular distributions of $\sigma(\theta)$, $A_y(\theta)$, $A_{yy}(\theta)$ and $A_{xx}(\theta)$ were measured in an angular range (1) Present address: Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510
(2) Supported by the U.S. Department of Energy, Office of High Energy and Nuclear Physics

Article published online by EDP Sciences and available at http://dx.doi.org/10.1051/jphyscol:1990647
of $15^\circ \leq \theta \leq 45^\circ$ in 2.5$^\circ$ steps. The absolute cross sections were estimated to have an uncertainty of 5.4%.

Angular distributions of $\sigma(\theta)$, $A_x$, $A_{yy}$ and $A_{xx}$ were measured for the $^{58}\text{Ni}$ polarized $(d,\alpha)^{56}\text{Co}$ reaction at $E_d = 22$ MeV using the Lamb-shift polarized ion source at the Munich MP accelerator laboratory. The Q3D magnetic spectrograph was used to detect the exiting $\alpha$ particles over an angular range of $10^\circ \leq \theta \leq 65^\circ$ in 5$^\circ$ steps with an experimental resolution of $= 12$ keV.

3 - ANALYSIS AND DISCUSSION

In the $^{32}\text{S}(d,^{3}\text{He})^{31}\text{P}$ reaction, the ground state ($1/2^+$) and 2.23 MeV ($5/2^+$) levels, known /5/ to proceed by $2s1/2$ and $1d5/2$ proton pickup respectively, were strongly excited. Angular distributions of $\sigma(\theta)$ showed an $\ell = 0$ shape for the ground state and $\ell = 2$ shape for the excited state. These transitions both represent cases of $j = \ell + 1/2$ and should be especially sensitive to the presence of a D-state in $^{3}\text{He}$ /6/. Figure 1 shows the measured $\sigma(\theta)$, $A_{xy}(\theta)$, $A_{yy}(\theta)$ for these transitions. The latter quantities, called analyzing cross sections, are chosen for comparison with theory because of their insensitivity, relative to analyzing powers, to the choice of OMP parameters in DWBA calculations. They are also largest and most sensitive to $\eta$ at angles where cross sections are large and such calculations are expected to most closely predict measured values.

Curves in fig. 1 are results of one-step exact finite-range DWBA calculations using the code TWOFNR with $\eta(^{3}\text{He}) = 0.048$ (solid curve) and $\eta(^{3}\text{He}) = 0$ (dashed curve). Cross section predictions have been adjusted by $< 20\%$ to match the measured cross section at forward angles for the ground state only. It has been shown for the $^{31}\text{P}(d,^{3}\text{He})^{30}\text{Si}$ g.s. transition at $E_d = 16$ MeV /6/ that the predicted cross sections and analyzing powers are not very sensitive to the choice of three-body wave function provided similar values are used for $D_2$ ($\eta$ is also the same to within 5% by the asymptotic approximation /7/). Since this insensitivity is also expected to appear in calculations for the $^{32}\text{S}(d,^{3}\text{He})^{31}\text{P}$ g.s. at 16 MeV an overlap integral $<d,p^{3}\text{He}>$ derived from a Woods-Saxon potential consistent with the $^{3}\text{He}$ separation energy was used in the present calculations.

Fig. 1 - Angular distributions for $\sigma(\theta)$, $A_{xy}(\theta)$, $A_{yy}(\theta)$ for states excited in the $^{32}\text{S}(d,^{3}\text{He})^{31}\text{P}$ reaction at $E_d = 16$ MeV. The solid curve results from exact finite-range DWBA calculations assuming $\eta(^{3}\text{He}) = -0.048$ while the dashed curve represents $\eta(^{3}\text{He}) = 0$. 
In the present analysis the best-fit value for \( q \) is determined by minimizing \( \chi^2 \) numerically as a function of \( \eta \) where \( q \) is generated using the techniques described in ref. /6/. Our result for states in \( ^{31}\text{P} \), \( q(\text{He}) = -0.048 \) is the average of these determinations weighted by the individual uncertainties. We estimate an uncertainty in \( \eta \) of \( \pm 0.006 \).

Our value of \( \eta \) is slightly larger in magnitude than obtained previously /6/, however, it is consistent with the recent theoretical findings of Friar et al. /3/ which predict a value of \( \eta(\text{He}) = -0.043 \pm 0.001 \). These calculations have been made using a Faddeev equation formalism and incorporating the Coulomb interaction. When our value is combined with the average value for \( \eta(t) \) given in ref. /2/ (\( \eta(t) = 0.051 \pm 0.004 \)), the ratio \( \eta(t)/\eta(\text{He}) = 1.11 \pm 0.15 \) is obtained, in agreement with expectations based on charge symmetry.

The \( ^{58}\text{Ni}(d,\alpha)^{56}\text{Co} \) reaction was chosen for a D-state parameter study since both the stretched state at 2.283 MeV having \( J^\pi = 7^+ \) and the 5+ level at 0.576 MeV are expected to be populated with essentially pure L transfers. The \((n,p)\) configuration expected to be transferred in populating the 7+ state is \((1f7/2, 1f7/2)\) leading to \( L = 6 \) transfer while the 5+ level is predicted /8/ to be populated by an almost unmixed transfer of \(-.58L = 4 \approx -.041L = 6 \) involving predominantly the \((2p3/2, 1f7/2)\) configuration. The assumption of a direct-pickup process works best for the states mentioned above since they are strongly populated. Finite-range DWBA calculations were carried out using realistic overlap functions generated by taking the Fourier transform of the \( d+d \) amplitudes in \( ^{4}\text{He} \) generated from the variational wave functions of Schiavilla et al. /1/ using the Argonne + Model VII interaction having \( D_2 = -0.16 \text{ fm}^2 \) and the Urbana + Model VII interaction \( (D_2 = -0.24 \text{ fm}^2) \). These overlap functions for S- and D-states are shown in fig. 2.

![Fig. 2 - S- and D-state overlap functions obtained from the Fourier transforms of fits to the d+d momentum distributions of ref. /1/](image)

Angular distributions of \( A_y(\theta) \), \( A_{xx}(\theta) \) and \( A_{yy}(\theta) \) for the two states in \( ^{56}\text{Co} \) are shown in fig. 3 in comparison with our calculations employing the Argonne interaction (solid line), the Urbana interaction (dashed line) and a Woods-Saxon overlap function involving an S-state term only (dotted line). The comparisons with the 5+ state indicate that the shape of the angular distributions are reasonably well predicted with calculations using OMP parameters taken from ref. /8/ and the predicted L-mixing amplitudes. There is not a great deal of variation in predictions using the Urbana and Argonne overlap functions, however. The DWBA calculations of tensor analyzing powers (TAP) for the 7+ state using the same OMP parameters, do show some variation with the choice of overlap function, especially for \( A_{xx} \). The comparisons with data indicate that the Argonne interaction provides a form factor which produces the closest comparison with experimental data. Other calculations indicate that overlap functions with the same \( D_2 \), e.g., Argonne and Woods-Saxon both with \( D_2 = -0.16 \text{ fm}^2 \) produce somewhat greater difference in shapes for the TAP calculations than observed in the \( ^{31}\text{P}(d,\text{He})^{30}\text{Si} \) study of ref. /6/. Further calculations
will be performed using OMP parameters obtained from fits to (d,d) and (α,α) elastic scattering data. The effects of the form factor of the heavy particle system will also be investigated.

Fig. 3 - Angular distributions of $A_y(θ)$, $A_{xx}(θ)$ and $A_{yy}(θ)$ for states populated in the $^{58}\text{Ni}(d,α)^{56}\text{Co}$ reaction at $E_d = 22$ MeV. The curves represent exact finite-range DWBA calculations using overlap functions generated using the Argonne+Model VII interaction (solid curve), the Urbana+Model VII interaction (dashed curve) and the Woods-Saxon potential (dotted curve).

In conclusion, TAP measurements for transfer reactions can be compared to exact finite-range DWBA calculations to test overlap functions derived from basic N-N interactions. For the $^{32}\text{S}(d,^3\text{He})^{31}\text{P}_{g.s.}$ reaction, the D-state sensitivity is enhanced in $σA_{xx}(θ)$ and $σA_{yy}(θ)$ observables especially at forward angles for $λ = 0$ transfers. Our analysis indicates that an overlap function with $η = -0.048$ provides a best fit in calculations of these observables. A preliminary analysis of the $^{58}\text{Ni}(d,α)^{56}\text{Co}$ reaction populating the $7^+$ state at 2.283 MeV indicates that of the two realistic overlap functions for the d + d system presented in ref. 11, the one based on the Argonne + VII interaction provides closest agreement with experimental TAP data.

REFERENCES