Role of tensor forces in the $^4He(\vec{d},{}^3He)^3H$ reaction

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Recent experimental polarization data on the $^4He(\vec{d},{}^3He)^3H$ reaction are analyzed. We performed a microscopic multichannel resonating group calculation and found sensitivity to the tensor force only for the tensor analyzing powers. In addition we fitted the experimental data by S-matrix elements and found good agreement between calculation and fit for the most important tensor-independent matrix elements and only fair agreement for the strongly tensor-dependent ones. Arguments for this finding are given.

The nucleon-nucleon interaction is certainly one of the most important topics of nuclear physics. Even though nucleon-nucleon experiments provide us with the most direct information about nuclear forces, some aspects can be investigated easier and more reliably in few-nucleon systems. This is true, in particular, for the spin-dependent part of the nuclear force manifesting itself through polarization observables, which in few-nucleon systems are by an order of magnitude larger than in nucleon-nucleon experiments. These observables can be measured with high accuracy allowing for deeper understanding of the nature of nuclear forces.[1,2] To this end, one has to resort to microscopic theoretical models which predict observables using nucleon-nucleon potentials. Some of the models proved to give satisfactory results for differential cross sections and vector analyzing powers.[1] On the other hand, there have only been scarce results for the tensor analyzing powers, and the reproduction of the experimental data is rather poor.[3,4] Here we address the problem of sensitivity of the various physical observables to the assumption made about the tensor forces. Recently, Vuaridel *et al.*[5] have measured, for the first time, tensor analyzing powers for the reaction $^4He(\vec{d},{}^3He)^3H$, including T_{21} in a measurement at $E_{c.m.}=23.4$ MeV ($E_{lab}=35.15$ MeV). This reaction seems well suited for studying the effects of the tensor force because there are tensor observables of the deuteron, and the spin zero of the alpha particle yields the most simple spin structure. The early theoretical calculations for this reaction were performed by Schütte *et al.*,[3,6] but no tensor analyzing powers were reported. In this paper we present a microscopic analysis of experimental results.

Usually, elastic α-d scattering and breakup reactions are described in the framework of the Faddeev theory[7] where one treats the α particle as elementary. For the reaction $^4He(d,{}^3He)^3H$, one cannot use this approach and, therefore, we determined the scattering matrix via the refined resonating group model. For details of this model we refer the reader to Ref. 8. The model is a microscopic one which allows us to treat many coupled channels. The radial dependence of the internal wave functions are determined by the Ritz variational principle in such a way that the Q values of the reactions are well reproduced. We use a standard nucleon-nucleon potential as given in Ref. 9. In the variation of the deuteron, ^3H, ^3He, and the α particle we allow only for relative S states. The details of the wave functions are quite similar to those of Ref. 3. For the relative momenta between fragments we allow up to $l=6$. Obviously, the results depend on which channels are taken into account. We report on two types of calculations: (i) a simplified one, the two-structure calculation, where only incoming (^4He+d) and outgoing ($^3H+{}^3He$) fragmentations were taken into account and; (ii) a calculation, including all 5 + 1 nucleon fragmentations like ^5Li+n, ^5He+p together with the first two excited states of ^5Li and ^5He, which from now on we will refer to as the full calculation.

The simplification of the former calculation is justified by the full calculation, which improves the agreement with experimental data but does not lead to any qualitative change in the calculated results (see Fig. 1). In particular, the shapes and the signs of tensor analyzing powers are not affected by the additional fragmentations. In both calculations the differential cross sections and the vector analyzing powers are reasonably well reproduced, but the calculations fail to describe the tensor observables.

To get an understanding on the role of the tensor effects, we choose to vary the tensor potential which acts between nucleons by multiplying it by a renormalization factor c. In addition to $c=1$, we use $c=0$ and $c=-1$. The effects of these drastically different assumptions on the tensor force are shown in Fig. 2. The differential cross section and vector analyzing power vary relatively little with the change of the tensor potential, whereas tensor analyzing powers are very sensitive. The residual tensor analyzing powers for $c=0$ are caused by the spin-orbit force. We consider the agreement of the data with the calculated T_{22} for $c=0$ as fortuitous.

The change of the factor c generally induces variation of S-matrix elements. In the following, these elements will be denoted by $S^{J}_{l_{\mathrm{in}} l_{\mathrm{out}} s_{\mathrm{out}}}$, where J is the total angular momentum, l_{in} and l_{out} are the incoming and outgoing orbital momenta, and s_{out} is the outgoing channel spin, the incoming channel spin always being 1. We found, in

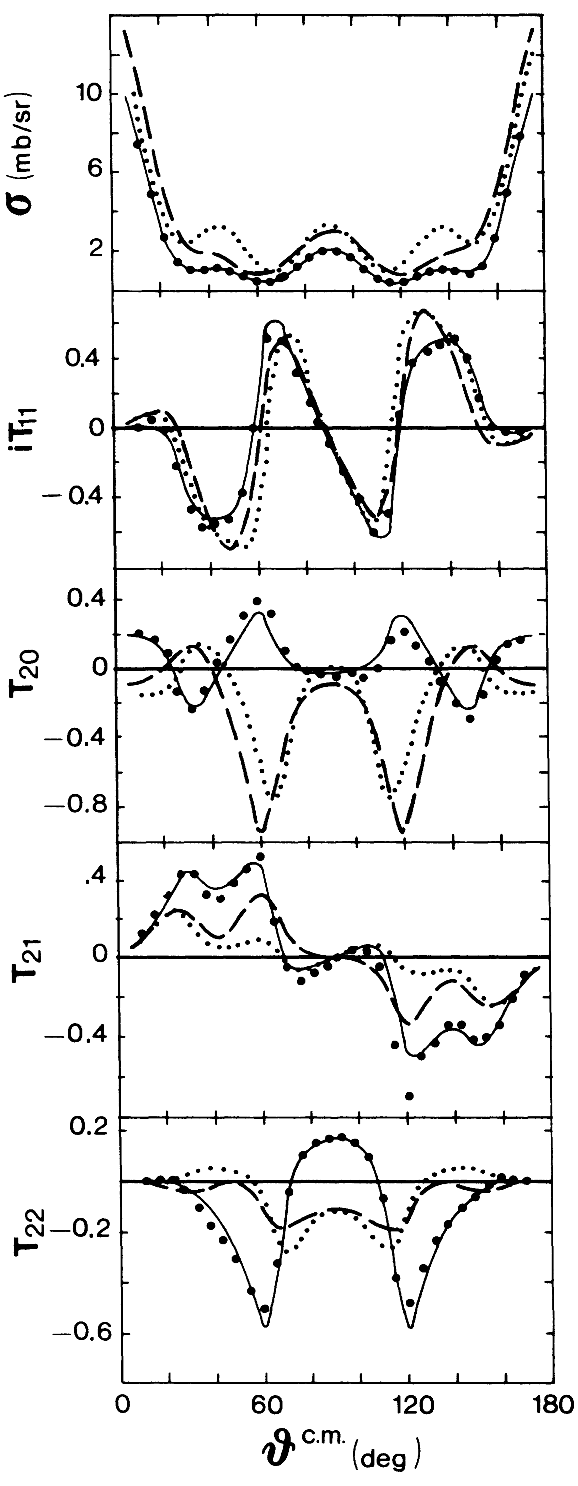

FIG. 1. Comparison of the two-structure (dotted line) and full calculations (dashed line) with experimental data (Ref. 5). The continuous line is the result of the fitting procedure described in the text.

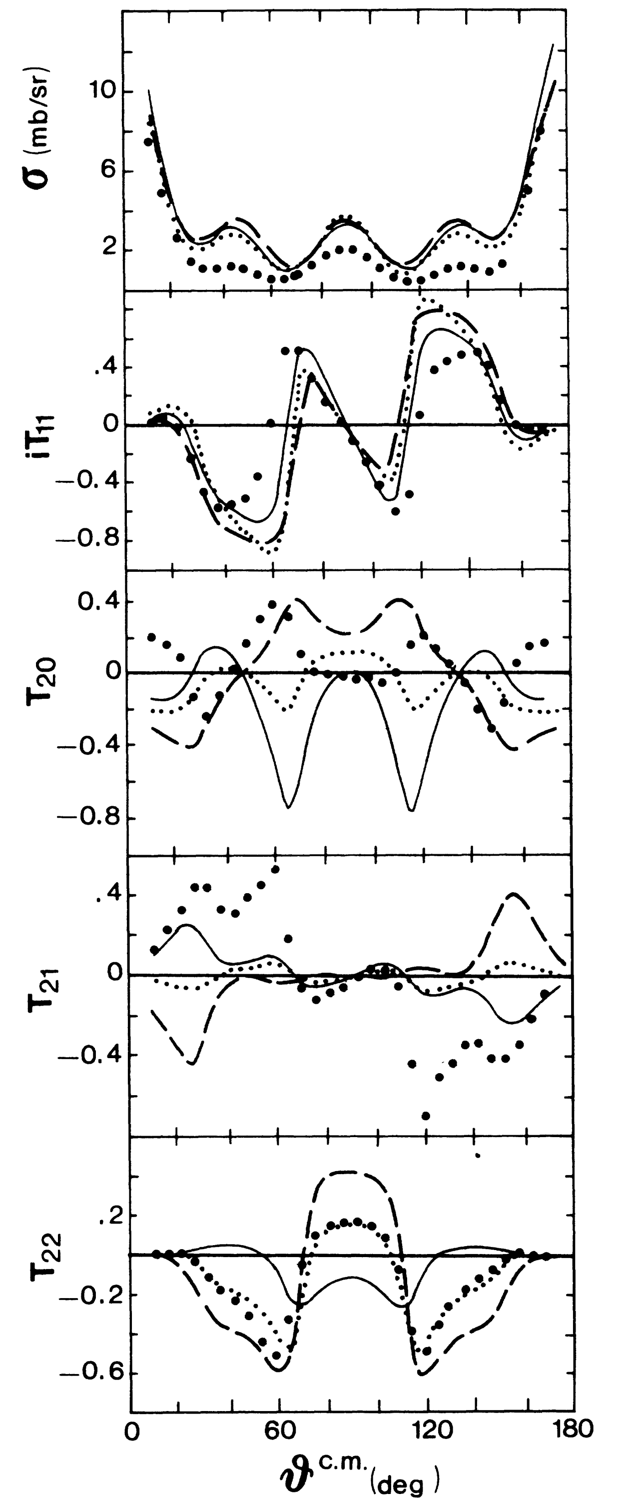

FIG. 2. The effect on observables of the variation of the tensor potential. The continuous line is the two-structure calculation; the dotted and dashed lines are calculations with $c=0$ and $c=-1$, respectively, as defined in the text.

our microscopic calculations, that the most important matrix elements ($S^1_{001}, S^3_{221}, S^3_{441}, S^4_{441}, S^5_{441}$) do not generally depend on the tensor force. An important exception is given by S^2_{221}, which is large and sensitive to the tensor force. On the other hand, the matrix elements with incoming and outgoing orbital angular momenta differing by two units originate solely from the tensor force. Therefore, one is tempted to determine the dominating matrix elements fitting the cross sections and the vector analyzing power times cross sections, and subsequently the tensor-dependent elements from the tensor analyzing powers times the cross sections. Such a fitting procedure would require using positive and also negative parity matrix elements yielding results without definite symmetry properties. The Barshay-Temmer theorem,[10] assuming ^{3}H and ^{3}He to be identical and isospin to be conserved, forbids interference of different parities in experimental situations like that of Ref. 5. From Figs. 1 and 2 it is apparent that this holds true on the level of 5–10%. Since our calculation yields large positive parity matrix elements and negative parity ones considerably smaller, we neglect negative parities in the fit and thus impose a definite symmetry for all observables. With these constraints, we fitted all the observables[5] at $E_{c.m.} = 23.4$ MeV presented in Figs. 1 and 2. The results of the fit are presented in Fig. 1, showing good agreement to the data. Small deviations originate from the fact that we have imposed a definite symmetry in the fit. In Table I we compare the fitted matrix elements with the results of the full calculations. In order to obtain a reasonable fit, we had to include matrix elements with $l = 6$ in the entrance and exit channels. If we compare calculated and fitted values for the matrix elements (see Table I), we note differences in the moduli and large deviations in the phases. From the behavior of these matrix elements under changes of the tensor potential, we found that there is no appropriate choice for the factor c, which would lead to reasonable agreement between calculated and fitted values. The matrix elements with $l_{in} = l_{out} + 2$, only due to the tensor force, turn out in the calculation to be three times larger in modulus than the ones corresponding to $l_{in} = l_{out} - 2$. This is due to the high threshold of the ^{3}H+^{3}He channel. The fitted matrix elements support this finding. In both cases matrix elements decrease with increasing J (or l). The remaining matrix elements agree both in modulus and in phase, except for the 3^+ matrix element with $l_{in} = l_{out} = 2$, which is too large. The corresponding matrix element describing elastic ^{3}H+^{3}He scattering[3] has to be small in order to reproduce the elastic data. This requires that the ^{3}H+^{3}He channel should be strongly coupled to others. In our restricted model spaces this channel couples preferentially to the corresponding $\alpha + d$ channel, thus yielding this large transition element. On the other side we know from the experimental analysis of the elastic α-d scattering[11] that the corresponding channel does not couple so strongly. We suppose that inclusion of further known positive parity structures[12] in ^{5}Li and ^{5}He would change the situation.

TABLE I. The comparison of the important S-matrix elements from the full calculation with those of the fit.

$S^J_{l_{in} l_{out} s_{out}}$	Calc. $\|S\|$	Calc. δ	Fit $\|S\|$	Fit δ
S^1_{001}	0.22	80	0.20	74
S^1_{221}	0.13	−18	0.15	26
S^2_{221}	0.29	14	0.31	10
S^3_{221}	0.55	15	0.30	24
S^3_{441}	0.21	56	0.17	63
S^4_{441}	0.20	60	0.20	65
S^5_{441}	0.18	58	0.18	57
S^5_{661}	0.04	45	0.04	11
S^6_{661}	0.04	46	0.03	43
S^7_{661}	0.08	46	0.08	30
S^1_{201}	0.25	27	0.15	26
S^1_{021}	0.09	−2	0.06	−60
S^3_{421}	0.14	−39	0.07	79
S^3_{241}	0.05	62	0.06	61
S^5_{641}	0.04	−40	0.06	−71
S^5_{461}	0.01	70	0.01	55

We have shown, quantitatively, the importance of the tensor interaction for the tensor analyzing powers, pointing out that some S-matrix elements, induced by the tensor force, are particularly relevant. Due to their different behavior under changes of the tensor potential, we have found that it is not possible to renormalize the tensor force by a simple factor in order to reproduce the data. This finding is in contrast to the results of Ref. 2 which reproduce the tensor analyzing powers in elastic $\alpha + d$ scattering without any tensor force. Inclusion of more fragmentations does not lead to any qualitative changes. From our calculation we conclude that this deficiency originates from the approximate treatment of the tensor interaction. Except for the ^{5}Li (^{5}He) ground and first excited states, all nucleons inside fragments are in relative S state and, hence, the tensor interaction mainly acts on the relative coordinate between fragments. To improve the description one has to allow for D-state admixtures in the internal wave functions, thereby increasing the complexity of the calculation beyond feasibility. Inclusion of (NN)-tensor forces at the level of internal D states in all fragments have only been reported, to our knowledge, in reactions like $d + d \to {}^3\mathrm{He} + n$.[13] The deviations of the fitted matrix elements and the calculated ones might be an indication of the importance of these admixtures. At the same time, it becomes clear from this study that differential cross section measurements alone, and maybe even vector analyzing power ones, are not sufficient to provide full information about microscopic forces, since their sensitivity to the tensor part of the potential is weak (see Fig. 2). In this context, systematic measurements of the tensor analyzing powers, like the ones of Ref. 5, are very helpful.

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