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^{4}He($\vec{d}$,p)n^{4}He reaction at 12 and 21 MeV deuteron energy

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The double differential cross section, the vector analyzing power, and the tensor analyzing powers for the ^{4}He($\vec{d}$, p)n^{4}He reaction were measured at 12 and 21 MeV deuteron energy and in steps of 5° between 15° and 75° in the laboratory system. The experimental results are compared with the Faddeev calculations, in which three cases for the treatment of the neutron-proton interaction are tested. As a result, we can demonstrate what interaction is effective on each observable.

[NUCLEAR REACTIONS ^{4}He ($\vec{d}$,p)n^{4}He, $E_d = 12.0$, 21.0 MeV; measured $d^2\sigma/d\Omega\, dE_p$, $iT_{11}(\theta)$, $T_{20}(\theta)$, $T_{21}(\theta)$, $T_{22}(\theta)$. Faddeev calculations.]

I. INTRODUCTION

Since a theoretical method for clarifying details of two-body interactions through the study of the three-body system was developed starting from Faddeev theory,[1] the nucleon-nucleon interaction has been investigated by researches on three-nucleon scattering. The most recent results on proton-deuteron elastic scattering,[2] including the results for polarization observables, give agreement between Faddeev calculations and experimental data for unpolarized differential cross sections, vector analyzing powers, and the tensor analyzing power T_{22}. However, it has been found that the tensor analyzing powers T_{20} and T_{21} are observables which are sensitive to details of the tensor force in the neutron-proton interaction, and calculations are not able to reproduce the experimental data.

For the reason described above, research on additional three-body systems is worthwhile for understanding the role of each two-body interaction in the framework of the Faddeev calculation. A candidate for this purpose is the study of observables up to the first order for spin variables in the deuteron-alpha system, in the energy region where the alpha particle can be regarded as a rigid, structureless particle. This system includes three distinct two-body interactions: neutron-proton, neutron-alpha, and proton-alpha. It is well known that the latter two have strong spin dependence. Therefore, it is of much interest to know the effect of these interactions on each observable. The reason why we have adopted the deuteron breakup reaction ^{4}He($\vec{d}$,p)n^{4}He, is described in the following.

For deuteron-alpha elastic scattering in the deuteron energy region between 4 and 25 MeV, Charnomordic *et al.*[3] have determined that the tensor force in the neutron-proton interaction is not essential, and all observables up to the first order for spin variables are explainable with the spin dependence of the nucleon-alpha interaction.

For the deuteron breakup reaction, ^{4}He($\vec{d}$,p)n^{4}He, the double differential cross section and the vector analyzing power iT_{11} have been measured thus far in the kinematically incomplete geometry.[4] Needless to say, the Faddeev theory is a powerful means to calculate the quantities in continuous spectra. One of the authors[5] performed calculations based on two-body interactions in which only the $^3S_1$ state was considered for the neutron-proton interaction, and obtained good agreement with the experimental double differential cross sections, especially with the vector analyzing power iT_{11} at $E_d^{\rm lab} = 15$ MeV. He has concluded that iT_{11} arises from the spin-orbit force in the nucleon-alpha interactions. Thereby he predicted the tensor analyzing powers T_{20}, T_{21}, and T_{22}.

In the present paper we will report the results of the first measurements on tensor analyzing powers in the ^{4}He($\vec{d}$,p)n^{4}He reaction at 12.0 and 21.0 MeV deuteron energy, together with the double differential cross section and the vector analyzing power, as well as Faddeev calculations with the inclusion of the tensor force in the neutron-proton interaction. A preliminary report was given in Ref. 6.

II. EXPERIMENTAL RESULTS

The apparatus used and procedures for the measurements were almost the same as described in Ref. 2. Therefore we will omit the details.

Figure 1 shows typical spectra obtained by a counter telescope in the measurement of the iT_{11} at $E_d^{\rm lab} = 12.0$ MeV. The peaks at the right end of the figure are those due to elastically scattered deuterons. The FWHM was 200 keV. The FWHM at $E_d^{\rm lab} = 21.0$ MeV was 300 keV. The continuous spectra are due to protons from deuteron breakup. The broad peaks at the right end of the continuous spectra are due to the unbound ^{5}He ground state. The cut at the left end of the continuous spectra is due to the finite thickness of the ΔE counter.

The closed circles in Figs. 2 and 3 indicate the measured double differential cross sections at $E_d^{\rm lab} = 12.0$ and 21.0 MeV, respectively. Each point is the average value in the interval of 200 keV at 12.0 MeV and of 300 keV at 21.0 MeV. Error bars include only the statistical error. The data were taken at angles from 15° to 75° in the lab-

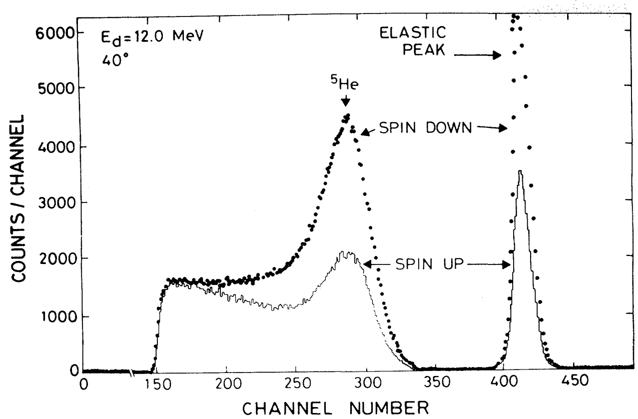

FIG. 1. Typical spectra of scattered particles in the measurement of the iT_{11} at $E_d^{lab}=12.0$ MeV and $\theta_{lab}=40°$. The full line indicates the case of the spin-up beam, and the dotted line the case of the spin-down beam.

oratory system in steps of 5°, though only four examples are shown in the figures. The meaning of the points and error bars in all the following figures are the same as described above. Total errors due to other sources were less than 1.5% for the double differential cross sections. Typical errors from each source were as follows: 0.2% for current integration, 0.2% for scattering centers in the target gas, 0.8% for the G factor, 0.6% for angle setting, 0.5% for the counting loss in the counter, and 0.5% for the counting loss in the circuits.

The closed circles in Figs. 4 and 5 indicate the measured iT_{11} at 12.0 and 21.0 MeV, respectively. The largest error other than the statistical error was the degree of polarization of the deuteron beams, which was measured by the quench-ratio method, amounting to 3%, which is common for the tensor analyzing powers described below. The other errors considered for the analyzing powers were those for angle setting and direction of the spin quantization axis. These were less than that of the degree of polarization of beams by an order of magnitude.

The closed circles in Figs. 6 and 7 indicate the measured T_{20} at 12.0 and 21.0 MeV, respectively. Total errors from sources other than counting statistics were less than 0.01.

The closed circles in Figs. 8 and 9 indicate the measured T_{21} at 12.0 and 21.0 MeV, respectively. The data in Figs. 10 and 11 indicate the measured T_{22} at 12.0 and 21.0 MeV, respectively. For both observables, the total errors from sources other than the counting statistics were of the same order of magnitude as the statistical error.

We remark here the fact that the dependence of the values of the analyzing powers at corresponding angles on the incident deuteron energy is small as a whole. If we dare to say, T_{21} has the strongest energy dependence, especially at angles larger than 60°.

III. FADDEEV CALCULATIONS

The potentials between the nucleon and alpha particle for $S_{1/2}$, $P_{3/2}$, and $P_{1/2}$ waves were based on the work of Cattapan *et al.*,[7] and are described in detail in Ref. 5, in

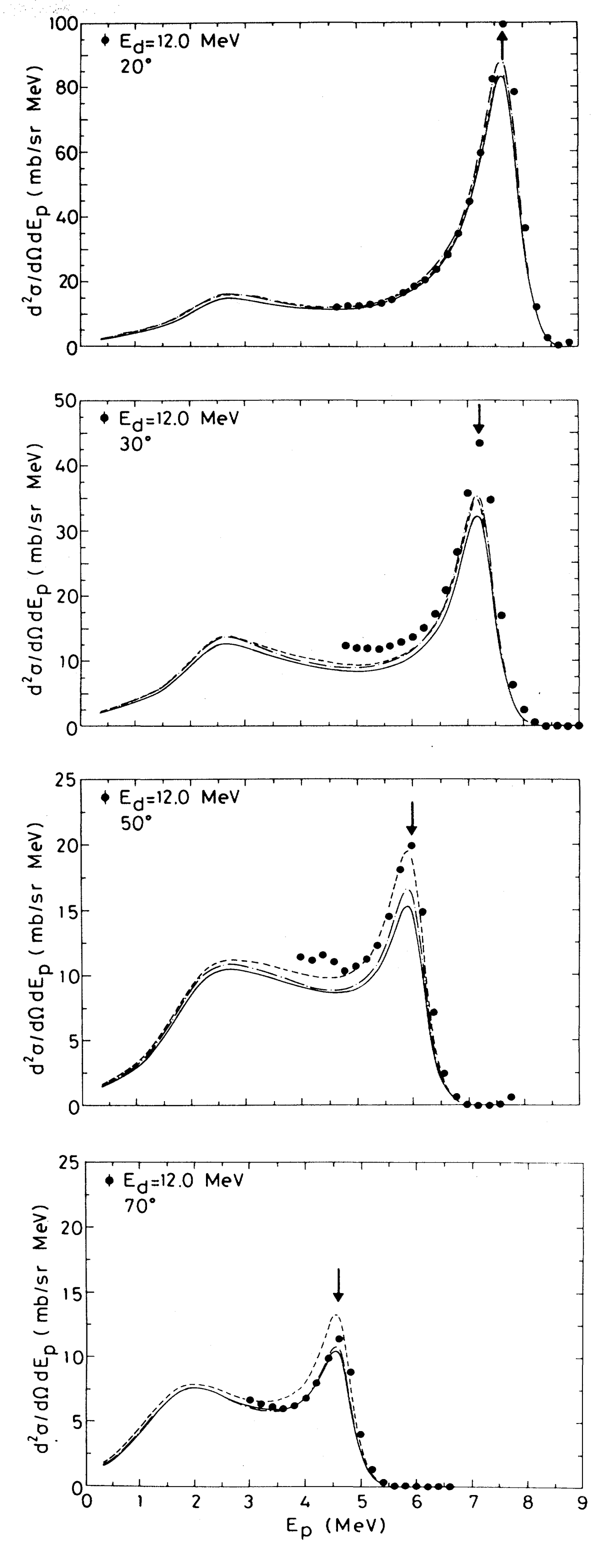

FIG. 2. The double differential cross sections at 12.0 MeV. The closed circles indicate the experimental data. The arrows indicate the position of the ^{5}He ground state. The dashed-dotted lines are the results of the "no tensor" case of the Faddeev calculation. The dashed and the full lines are those of the "impulse tensor" and the "full tensor" cases, respectively.

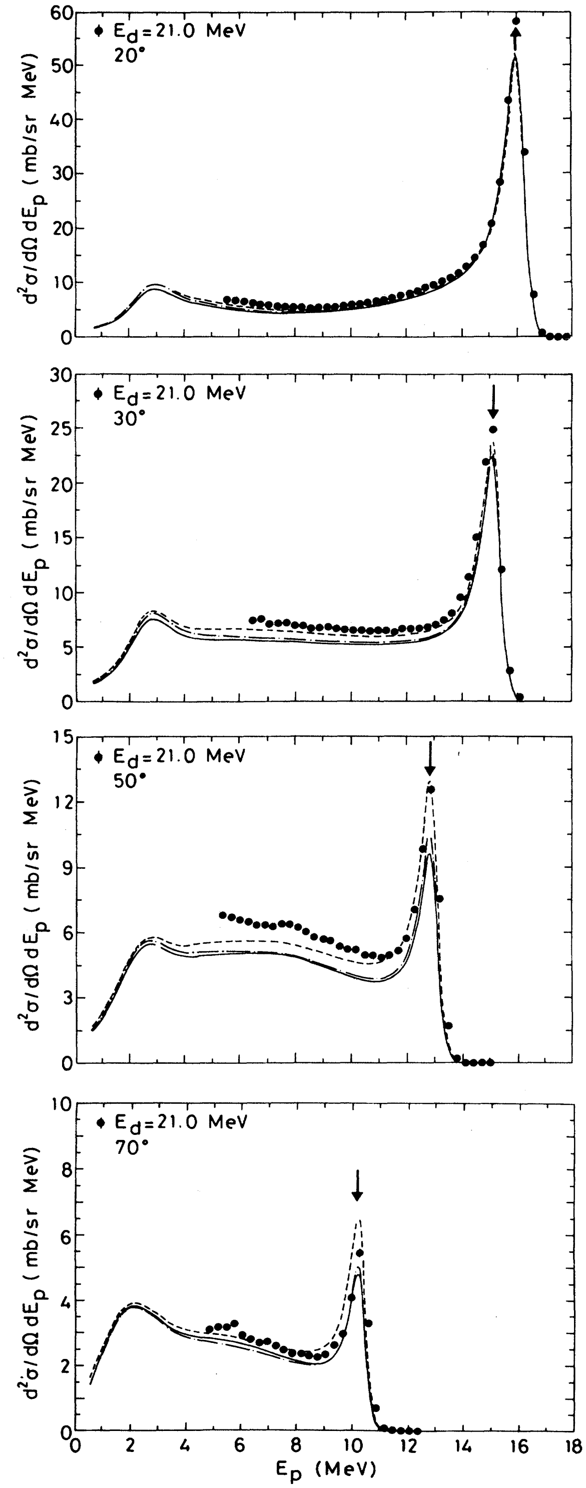

FIG. 3. The double differential cross sections at 21.0 MeV. See the caption of Fig. 2.

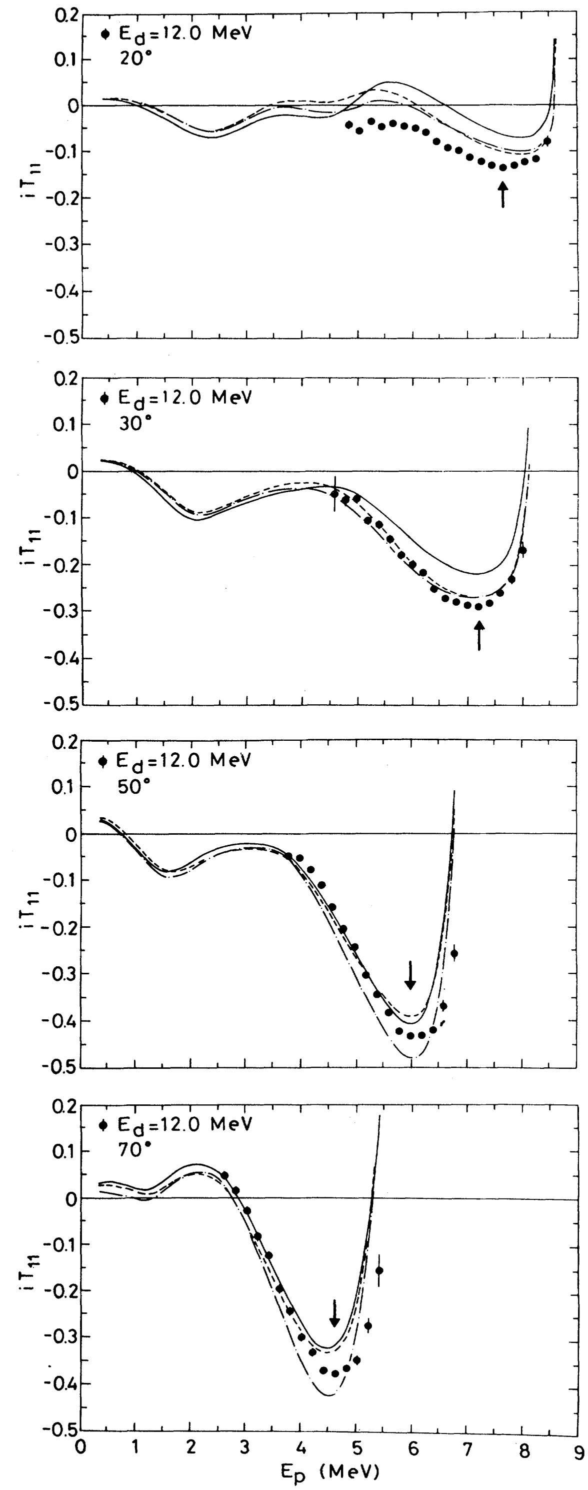

FIG. 4. The iT_{11} at 12.0 MeV. See the caption of Fig. 2.

which only the $^3S_1$ state was considered for the neutron-proton interaction based on the work of Cahill and Sloan.[8] Hereafter we denote this case as the "no tensor."

As described in the next section, measured tensor analyzing powers cannot be fitted by the "no tensor" calculation. Therefore we felt the need for the inclusion of the $^3D_1$ state in the neutron-proton interaction. The effect of the $^3D_1$ state was examined through two steps. Firstly, only in the single scattering term of the Alt-Grassberger-Sandhas (AGS) equation[9] was the $^3D_1$ state of the deu-

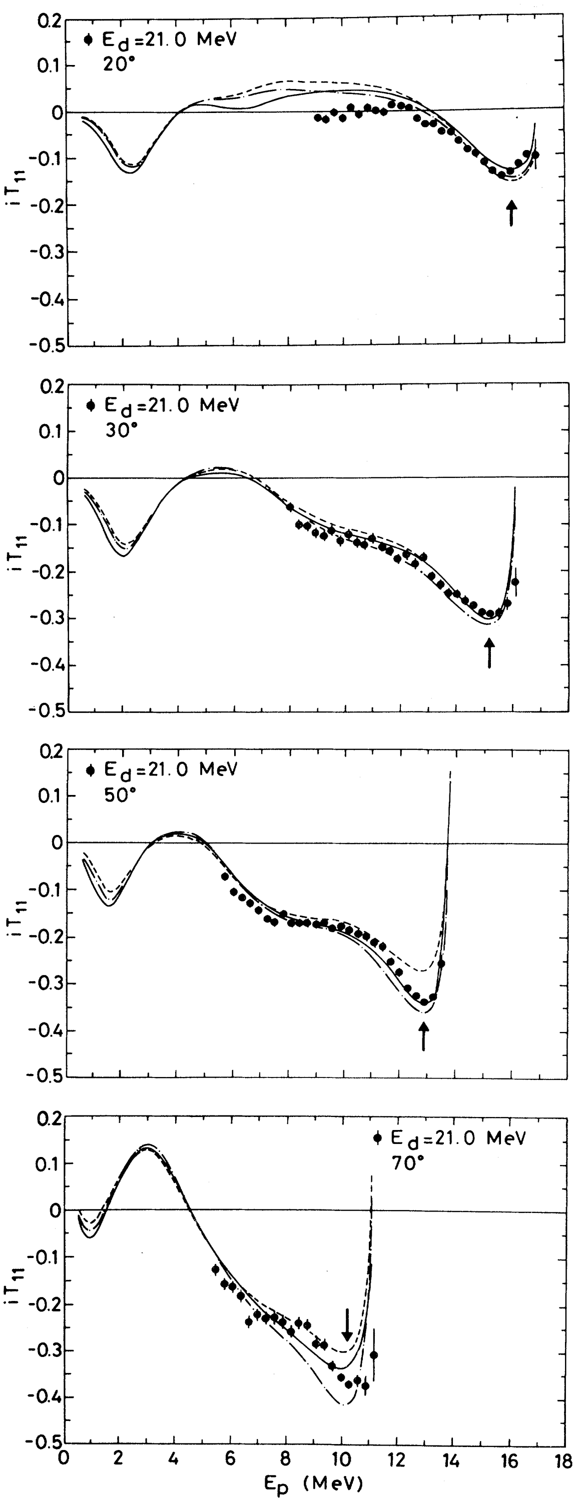

FIG. 5. The iT_{11} at 21.0 MeV. See the caption of Fig. 2.

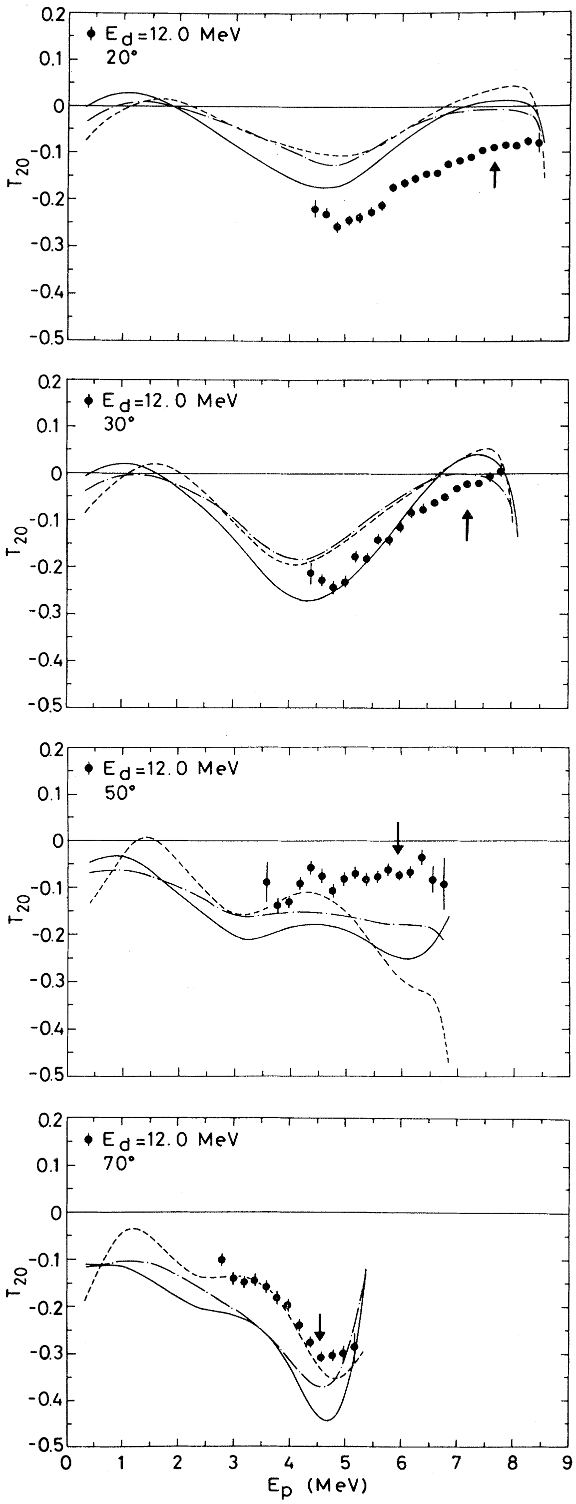

FIG. 6. The T_{20} at 12.0 MeV. See the caption of Fig. 2.

teron ground state added, corresponding to an impulse approximation. Hereafter we denote this case as the "impulse tensor." Secondly, the tensor force was introduced in the neutron-proton interaction, and the multiple scattering term was taken into consideration fully. Hereafter we denote this case as the "full tensor." The potential for the tensor force was a separable potential of Yamaguchi type with a 5.5% D state probability based on Phillips's work.[10]

As a result, we have three cases which reveal the quan-

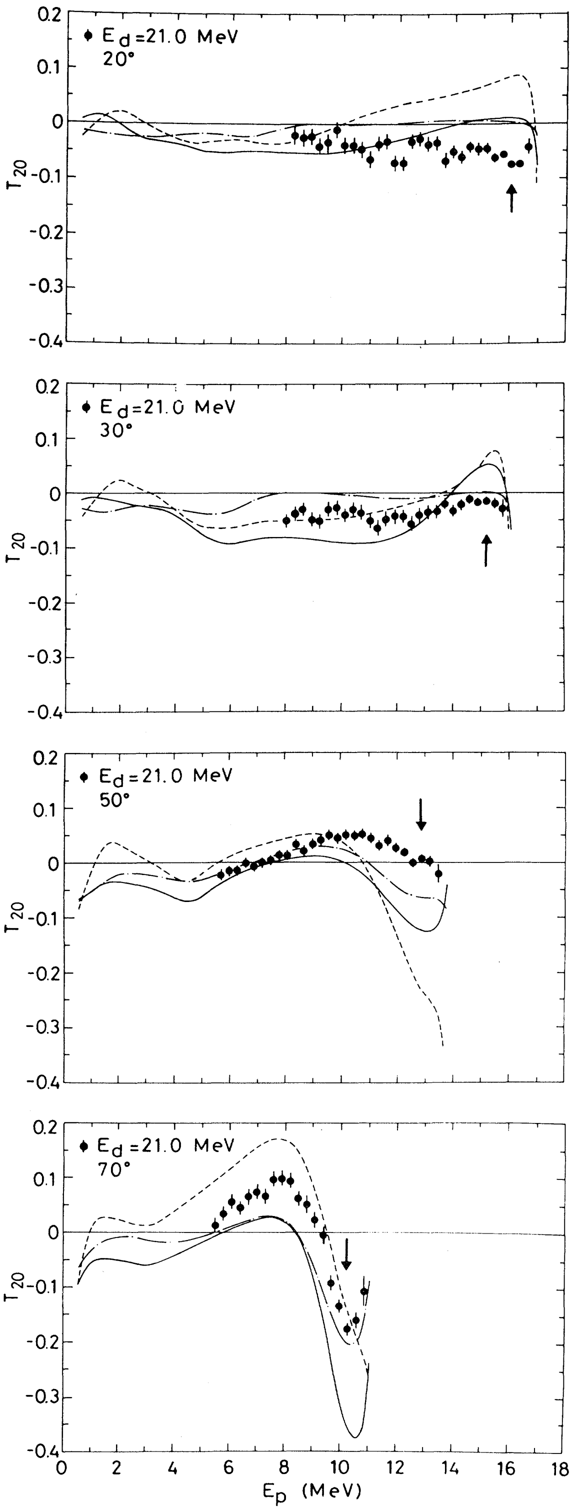

FIG. 7. The T_{20} at 21.0 MeV. See the caption of Fig. 2.

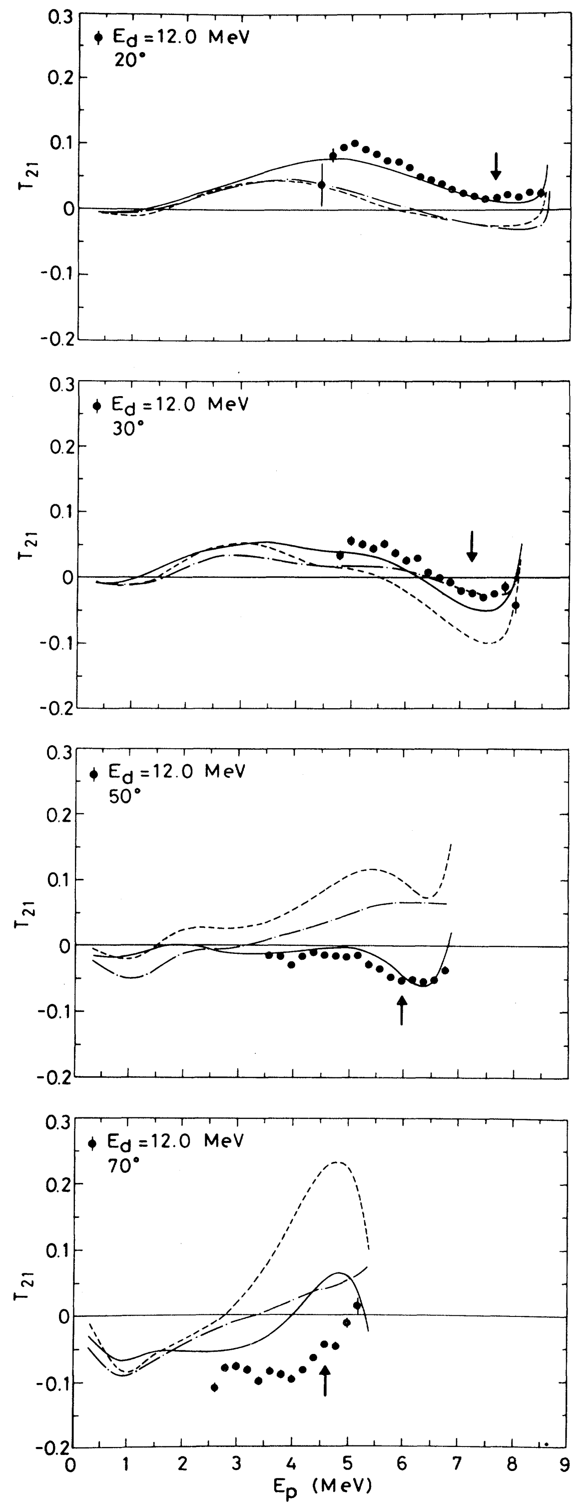

FIG. 8. The T_{21} at 12.0 MeV. See the caption of Fig. 2.

titative contributions from added terms to the observables discussed in this work, especially to the tensor analyzing powers. Namely, the $^{4}He(\vec{d},p)n\,^{4}He$ reaction is a very suitable reaction to study through such a procedure, because it is rewarding for this purpose, as discussed in the next section.

The results of calculations are indicated in Figs. 2—11, dashed-dotted lines corresponding to the "no tensor," dashed lines to the "impulse tensor," and full lines to the "full tensor" case.

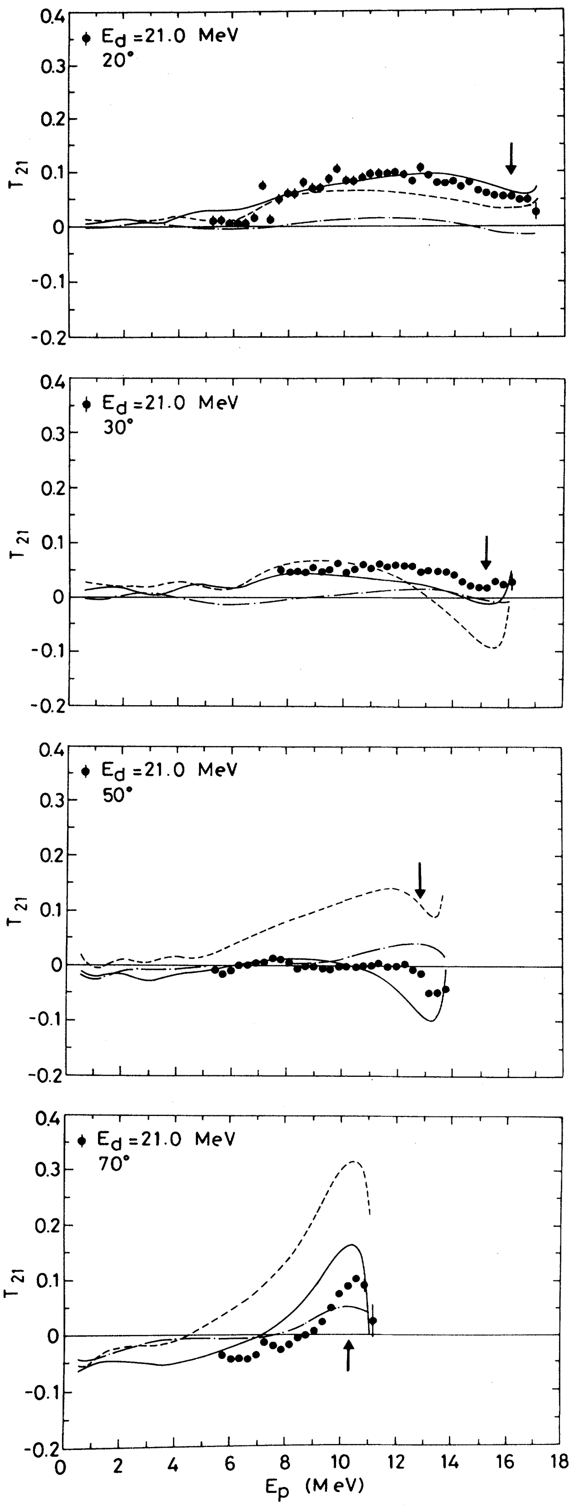

FIG. 9. The T_{21} at 21.0 MeV. See the caption of Fig. 2.

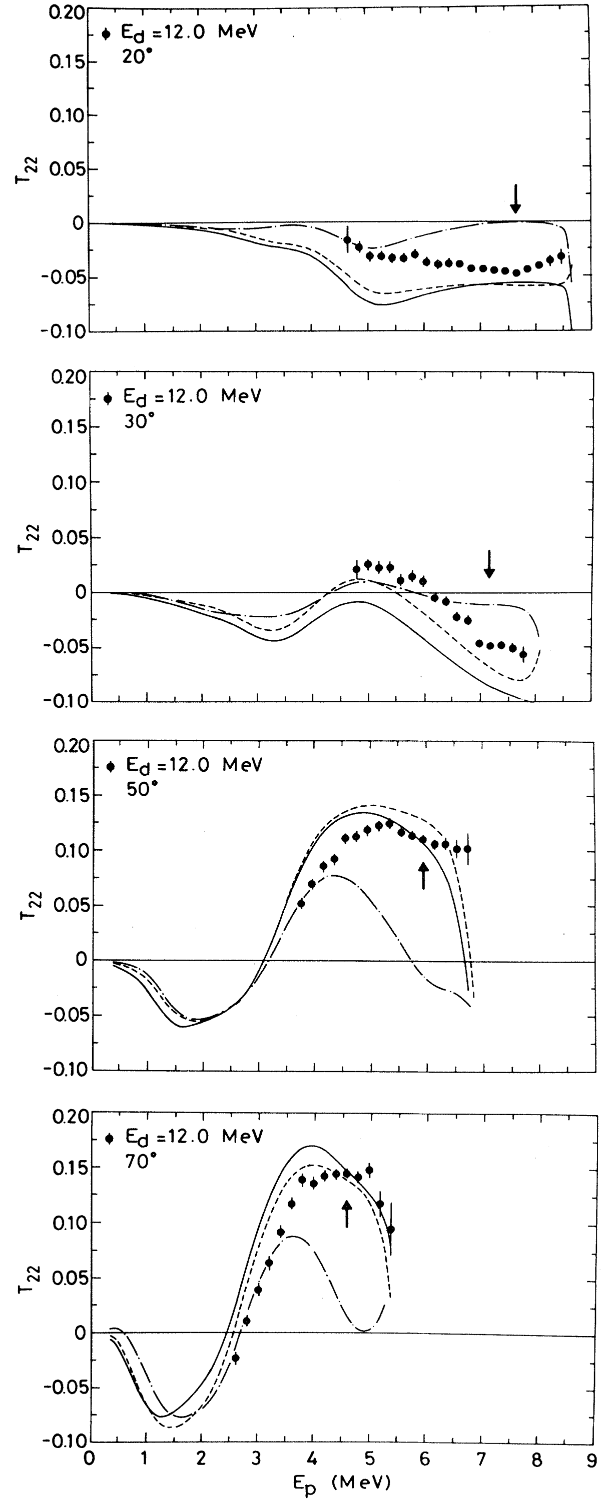

FIG. 10. The T_{22} at 12.0 MeV. See the caption of Fig. 2.

IV. DISCUSSION

By examining Figs. 2—5, the experimental double differential cross section and the experimental vector analyzing power are fitted by the calculations without the tensor force in the neutron-proton interaction, as has been discussed by Koike in Ref. 5.

However, for the double differential cross section, the inclusion of the "impulse tensor" increases the amount and somewhat improves the fit as a whole. The case of

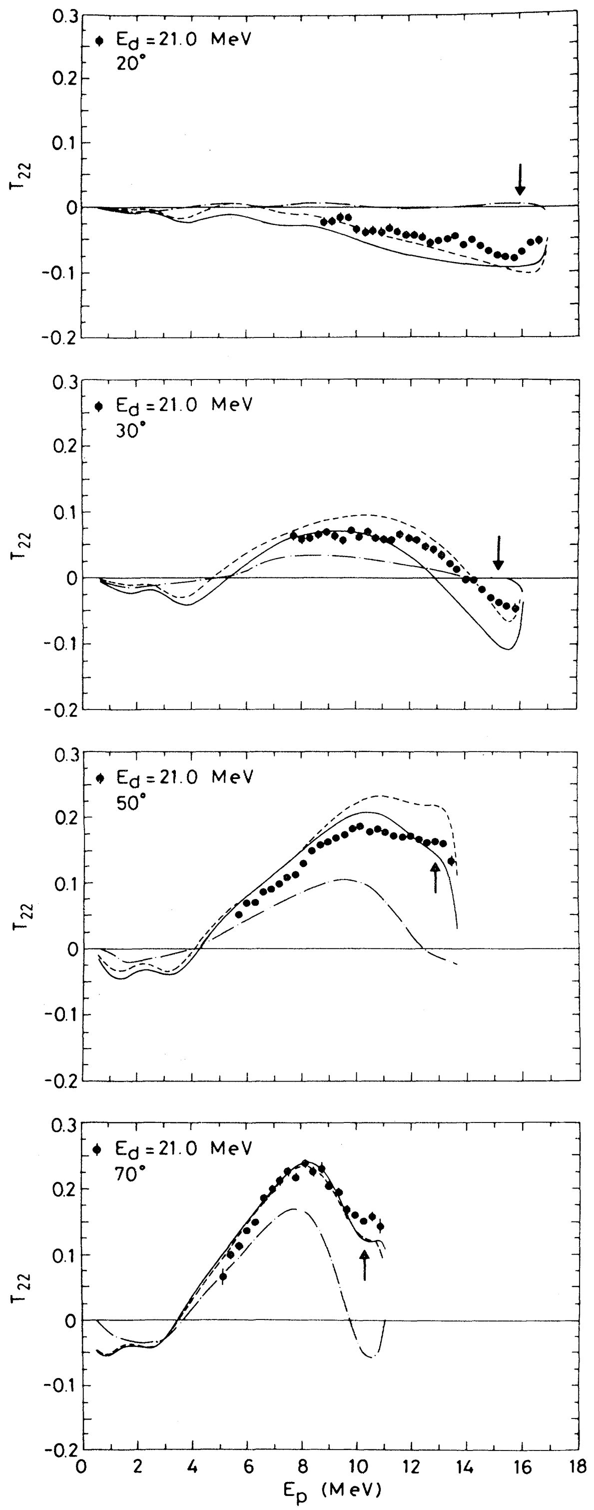

FIG. 11. The T_{22} at 21.0 MeV. See the caption of Fig. 2.

the "full tensor" decreases the amount by a little more than the increase in the case of the "impulse tensor."

For the vector analyzing power, calculated values of three cases are not altered from each other. It is worth noting that the calculated values of the "full tensor" at 21.0 MeV reproduce the experimental data fairly well.

By examining Figs. 6–11, none of the experimental tensor analyzing power is reproduced by the "no tensor" calculation. The spin dependent interaction between nucleon and alpha particle in general gives a smaller absolute value for the tensor analyzing power than the experimental one. Therefore we examined the calculations of the "impulse tensor" and the "full tensor."

For the tensor analyzing power T_{20}, the agreement between experimental and calculated results is poor despite the inclusion of the tensor force in the neutron-proton interaction. But the situation is not hopeless, because the experimental gradient dT_{20}/dE_P is followed by the calculated one, and the calculated values reproduce the experimental data at some angles and energies.

In contrast to the case of the T_{20}, the calculated T_{21} with the "full tensor" succeeds in showing us an overall fit to the experimental data for T_{21}. A remarkable fact is that the large change of the calculated value of the T_{21} from the case of "no tensor" to the case of "impulse tensor" is compensated partly or excessively by the inclusion of the multiple scattering term in the case of the "full tensor," demonstrating the effect of the multiple scattering term.

Another interesting feature is seen in the calculated values of T_{22}. The case of the "impulse tensor" already gives a marked improvement of the fit to the experimental data, and the difference between the cases of the "impulse tensor" and the "full tensor" is very small. Almost no contribution from the multiple scattering term results in the T_{22}.

V. CONCLUSION

It is demonstrated that the Faddeev calculation is a powerful method to analyze the breakup reaction into three bodies.

By making calculations in three steps as described above, we can demonstrate what interaction is effective on each observable. Namely, the double differential cross section and the vector analyzing power in the ^{4}He($\vec{d}$,p)n^{4}He reaction is explainable without the tensor force in the neutron-proton interaction. However, for the tensor analyzing powers the inclusion of the tensor force in the neutron-proton interaction is essential. It is interesting that T_{22} does not invoke the multiple scattering term, and the T_{21} is an observable on which the multiple scattering term has an important effect.

As for T_{20}, we cannot discuss this case any further at the present time. However, in view of the simplicity of the interactions used in the present work, there remains the possibility of improvement in the situation by use of more sophisticated interactions.

The quite recent results of kinematically complete measurements of the ^{4}He($\vec{d}$,αp)n reaction at 12 and 17 MeV have been compared with the Faddeev calculation of the "no tensor" case, resulting in conclusions similar to those of the present "no tensor" case.[11] The Faddeev calculation with the inclusion of the tensor force in the neutron-proton interaction for kinematically complete geometry is now required.

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[1]L. D. Faddeev, Zh. Eksp. Teor. Fiz. 39, 1493 (1960) [Sov. Phys.—JETP 12, 1014 (1961)].

[2]M. Swada, S. Seki, K. Furuno, Y. Tagishi, Y. Nagashima, J. Schimizu, M. Ishikawa, T. Sugiyama, L. S. Chuang, W. Grüebler, J. Sanada, Y. Koike, and Y. Taniguchi, Phys. Rev. C 27, 1932 (1983).

[3]B. Charnomordic, C. Fayard, and G. H. Lamot, Phys. Rev. C 15, 864 (1977).

[4]L. G. Keller and W. Haeberli, Nucl. Phys. A172, 625 (1971); H. Nakamura, H. Noya, S. E. Darden, and S. Sen, *ibid.* A305, 1 (1978).

[5]Y. Koike, Nucl. Phys. A337, 23 (1980).

[6]M. Ishikawa, S. Seki, K. Furuno, Y. Tagishi, M. Sawada, T. Sugiyama, K. Matsuda, J. Sanada, and Y. Koike, J. Phys. Soc. Jpn. 51, 1327 (1982).

[7]G. Cattapan, G. Pisent, and V. Vanzani, Nucl. Phys. A241, 204 (1975).

[8]R. T. Cahill and I. H. Sloan, Nucl. Phys. A165, 161 (1971).

[9]E. O. Alt, P. Grassberger, and W. Sandhas, Nucl. Phys. B2, 167 (1967).

[10]A. C. Phillips, Nucl. Phys. A107, 209 (1968).

[11]I. Slaus, J. M. Lambert, P. A. Treado, F. D. Correll, R. E. Brown, R. A. Hardekopf, N. Jarmie, Y. Koike, and W. Grüebler, Nucl. Phys. A397, 205 (1983).