whether the $^3S_1$ FSI is dominant or not, because it was carried out only for a particular direction of the relative n-p motion. However, we believe from the present result that the analyzing power does not vary so rapidly with this direction of motion if the $^3S_1$ FSI is dominant. A kinematically complete polarization calculation and/or experiment should be very helpful to solve this problem. From the present results it appears feasible and useful to continue these measurements with use also of tensor-polarized deuterons in order to obtain these data as a function of energy. Faddeev calculations[5] predict significant changes to lower energies and one can expect to see the influence of the 1^+ resonance of ^6Li as a three-body resonance on the breakup, especially on the polarization observables.

This work was supported in part by Bundesministerium für Forschung und Technologie, West Germany.

[a]Now at Kernforschungsanlage, Jülich, D-5170 Jülich, West Germany.

[b]Now at Institut fur Experimentalphysik, Universität Hamburg, D-2000 Hamburg, West Germany.

[1]P. E. Shanley, Phys. Rev. 187, 1328 (1969).

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

[3]Y. Koike, Progr. Theor. Phys. 59, 87 (1978).

[4]Y. Koike, Nucl. Phys. A301, 411 (1978), and in *Few Body Systems and Nuclear Forces I*, edited by H. Zingl, M. Haftel, and H. Zankel, Lecture Notes in Physics, Vol. 82 (Springer-Verlag, Berlin, 1978), p. 320.

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

[6]H. Eichner, H. Stehle, and P. Heiss, Nucl. Phys. A205, 249 (1973).

[7]K. Prescher, W. Bretfeld, W. Burgmer, H. Eichner, H. J. Helten, H. Klein, H. Kretzer, H. Stehle, and W. W. Wohlfarth, Nucl. Phys. A268, 142 (1977).

[8]H. Oswald, W. Burgmer, D. Gola, C. Heinrich, H. J. Helten, H. Paetz gen. Schieck, and Y. Koike, in Proceedings of the Fifth International Symposium on Polarization Phenomena in Nuclear Physics, Santa Fe, 1980 (to be published).

[9]V. Bechtold, L. Friedrich, P. Ziegler, R. Aniol, G. Latzel, and H. Paetz gen. Schieck, Nucl. Instrum. Methods 150, 407 (1978).

[10]G. G. Ohlsen, P. A. Lovoi, G. C. Salzman, U. Meyer-Berkhout, C. K. Mitchell, and W. Grüebler, Phys. Rev. C 8, 1262 (1973).

[11]W. Grüebler, P. A. Schmelzbach, V. König, R. Risler, and D. Boerma, Nucl. Phys. A242, 265 (1975).

[12]D. Gola *et al.*, to be published.

[13]Y. Koike, in Ref. 8.

[14]C. Stolk and J. A. Tjon, Phys. Rev. Lett. 39, 395 (1977).

Evidence for Deuteron *D*-State Effects on the Polarization of the 2.58-MeV State in ^{57}Ni Excited in the (p,d) Reaction

Hajime Ohnuma, Norio Kishida,[a] Jirohta Kasagi,[b] and Toshiyuki Kubo[a]
Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152, Japan

and

Masaharu Yasue
Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo 188, Japan

(Received 22 September 1980)

Deuteron-γ angular correlation measurements and their analysis indicate significant effects of the deuteron D state on the spin-statistical tensors of the 2.58-MeV $(\frac{7}{2}^-)$ state in ^{57}Ni excited in the reaction ^{58}Ni$(p,d)^{57}$Ni at an incident energy of 30 MeV.

PACS numbers: 25.40.Gr, 24.70.+s

Since the early works of Johnson and Santos[1] and of Delic and Robson[2] the role of the deuteron D state in direct (d,p) and (p,d) reactions has been the subject of many theoretical and experimental studies. It now seems well established that the deuteron D state has only small effects on differential cross sections at low energies, while it has significant effects on tensor analyzing powers.[3] The D-state effects on cross sections are shown[4] to be quite important at several-hundred megaelectronvolts, where large momentum transfers are involved. The D-state effects on the polarization transfer have also been reported.[5] The polarizations, or, more strictly, the spin-statistical tensors, of the residual nuclear states also give information on the reaction amplitudes, and this information is independent of that contained in the quantities mentioned above.[6] Therefore it is very interesting to see how important the D-state effects are on the polarization of the states excited in (p,d) or (d,p) reactions.

We have measured the d-γ angular correlations in the reaction $^{58}\mathrm{Ni}(p,d\gamma)^{57}\mathrm{Ni}$ at $E_p = 30$ MeV, and observed for the first time a clear indication of the deuteron D-state effects on the polarization of a residual nuclear state, the 2.58-MeV $(\frac{7}{2}^-)$ state in ^{57}Ni. This state has the largest pickup cross section among the ^{57}Ni states. Furthermore, it is known[7] to decay only to the ground state $(\frac{3}{2}^-)$ by a pure $E2$ transition. Therefore the analysis is free from the uncertainties in mixing ratio and the estimation of sum-peak intensities.

The measurement was made with use of a 30-MeV proton beam from the Institute for Nuclear Study sector-focusing cyclotron. After passing through the target, the beam was focused again by a pair of quadrupole magnets and lead to a beam dump 4 m away from the target chamber. Careful beam transport and shielding enabled us to reduce the background counting rate less than 2% in γ-ray singles spectra. The target was a 2.4-mg/cm^2-thick nickel foil enriched to 99.8% in ^{58}Ni. Four sets of Si counter telescopes were used to detect deuterons, and four 5×5 cm^2 NaI-(Tl) detectors were placed in the reaction plane to detect γ rays. The relative efficiencies of the γ-ray detectors, as well as the geometrical eccentricity, were checked by measuring residual activities in the target. They were found to be identical within the 2% statistical errors. Energy signals and timing signals from these detectors were fed into a TOSBAC-40C computer to sort out coincidence events. Signals were also recorded on magnetic tape for later off-line analysis. The time resolution was typically 10 ns, much smaller than the beam burst interval ($\simeq$60 ns). Accidental-coincidence events amounted to as high as 15% of true events at 10 nA of the beam current, and were subtracted from the spectra.

The differential cross section and analyzing power obtained for the 2.58-MeV state at the same incident energy[8] are shown in Fig. 1, which is included here to illustrate the fact that the theory gives a good account of these standard observables. Figure 2 shows the angular correlation functions measured at $\theta_d^{\mathrm{c.m.}} = 25°$, 45°, and 65°. These angles correspond to the first maximum, the first minimum, and the second maximum of the cross-section angular distribution. The solid and dashed curves in Figs. 1 and 2 represent exact-finite-range (EFR) distorted-wave Born-approximation (DWBA) calculations with and without the D-state effects. The EFR DWBA code TWOFNR[9] has been modified[10] to include the D-state calculations. The n-p interaction, which is used to describe the transfer reaction as well as to generate the deuteron internal wave function,

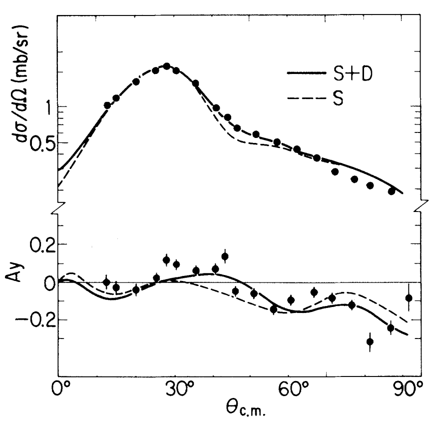

FIG. 1. Differential cross section $d\sigma/d\Omega$ and analyzing power A_y for the reaction $^{58}\mathrm{Ni}(p,d)^{57}\mathrm{Ni}$ (2.58 MeV, $\frac{7}{2}^-$) at $E_p = 30$ MeV compared with the EFR DWBA calculations with (solid curves) and without (dashed curves) the D state. The distorting potential parameters are taken from Refs. 12 and 13.

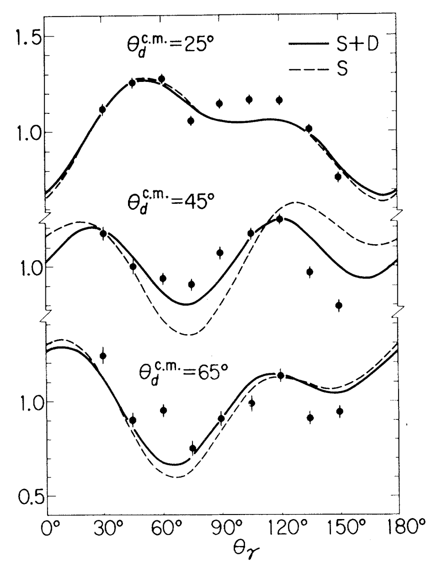

FIG. 2. Experimental d-γ angular correlations measured in the reaction plane for the 2.58-MeV state at three different angles of deuterons compared with the EFR DWBA calculations. See caption for Fig. 1.

is taken to be the Reid soft-core potential.[11]

Distorting potential parameters used in the calculations are taken from Greenlees and Pyle[12] and Baker *et al.*[13] Nonlocality of the potentials has been included in the local-energy approximation. The form factor is generated by the usual separation energy method. Finite-solid-angle corrections, although small, have been made to the calculated correlation functions to facilitate direct comparison with the data.

The program has been tested for several choices of the integration mesh size and the integration range. The results are found to be rather sensitive to these parameters in the integration. With a proper choice of the parameters, the program reproduces the results of Delic and Robson.[2] In particular, the integration range in the present calculation is enough to cover the interaction range, as the D_2 value[14] obtained here is 0.483 fm^2 and close enough to the value 0.484 fm^2 given by Knutson and Haeberli[15] for the Reid soft-core potential.

Inclusion of the deuteron D state slightly increases the calculated cross sections around 45°, as shown in Fig. 1. Such an effect was first noticed by Johnson and Santos[1] as a possible origin of J dependence. The D-state effects on vector analyzing power are also small, but somewhat improve the fit to the data. On the other hand, the D-state effects are appreciable on the correlation function for $\theta_d^{\text{c.m.}} = 45°$, and significantly improve the fit to the data. Near the maxima of cross sections, at 25° and 65°, the D-state effects on the correlation functions are small, although slight improvement of the fit is seen at 65°.

The D-state effects observed in the fit to the correlation data at 45° are not related to a specific choice of potential parameters. This can be seen in Fig. 3, where examples of the correlation functions calculated with different sets of deuteron parameters are compared with the data. The best fit to the experimental data is obtained with the adiabatic potential for deuterons, $D3$, although the fits to the cross section and analyzing power data are slightly worse. Irrespective of the potential parameters used, the 45° correlation data could not be explained without the deuteron D-state effects.

It is not difficult to understand why the D-state effects are important to the correlation functions even when the effects on the cross section and vector analyzing power are small: The cross sections are insensitive to the D-state effects at low energies, since primary contributions to the cross sections come from the spin-independent parts of the distorting potentials and the central n-p interaction. Vector polarization and analyzing power are largely affected by the spin-orbit parts and the absorptive parts of the distorting potentials through the modification of the distorted waves. In order to see the D-state effects on the vector polarization and vector analyzing power, therefore, one must eliminate the contribution from the spin-orbit potentials and the absorption. This can be achieved in some special cases[19] by measuring both the polarization and the analyzing power. On the other hand, the angular momenta of target and residual nuclei enter DWBA calculations through the form factors, the product of the residual interaction, and the initial- and final-state wave functions. The inclusion of the tensor force in the residual n-p interaction (and consequently the D state in the deuteron wave function) directly modifies the form factor and the angular momentum coupling therein. Thus the polarization of the residual nuclear state can be sensitive to the D-state effects when the major components of the reaction amplitudes are relatively suppressed, namely at the minima of cross-section angular distributions.

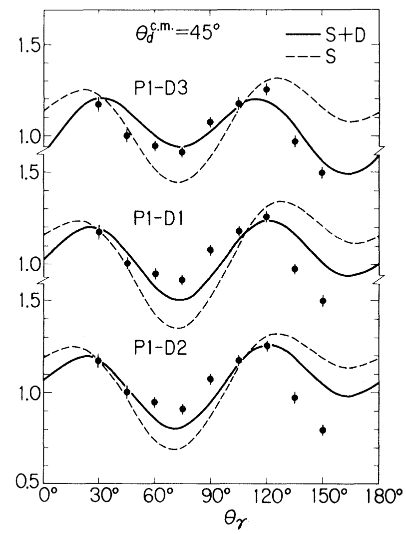

FIG. 3. Correlation functions calculated for $\theta_d^{\text{c.m.}} = 45°$ with different deuteron potentials compared with the data. The proton potential of Ref. 12 is used. The deuteron potentials $D1$ and $D2$ are taken from Refs. 13 and 16, respectively. The deuteron potential $D3$ is the adiabatic potential constructed from the proton and neutron potentials of Ref. 17, following the prescription given in Ref. 18.

In summary, a clear indication of the effects of the deuteron D state on the polarization of the 2.58-MeV ($\frac{7}{2}^-$) state has been obtained in the ^{58}Ni($p, d\gamma$) angular-correlation measurement at an incident energy of 30 MeV. The importance of the D-state effects to the polarization of the residual nuclear states can be understood by examining the DWBA formalism.

This work was supported in part by Japan Ministry of Education Grant-in-Aid for Scientific Research B No. 346010. All the EFR DWBA calculations were done with the FACOM-230-75 computer at the Institute of Physical and Chemical Research, and off-line data analysis was done with the FACOM-M-180-II computer at the Institute for Nuclear Study.

[(a)]Present address: Institute for Physical and Chemical Research, Wako-shi, Saitama 351, Japan.

[(b)]Present address: Cyclotron Laboratory, Michigan State University, East Lansing, Mich. 48824.

[1]R. C. Johnson and F. D. Santos, Phys. Rev. Lett. 19, 364 (1967).

[2]G. Delic and B. A. Robson, Nucl. Phys. A156, 97 (1970), and A232, 493 (1974).

[3]W. Haeberli, J. Phys. Soc. Jpn. Suppl. 44, 435 (1978).

[4]E. Rost and J. R. Shepard, Phys. Lett. 59B, 413 (1975).

[5]A. K. Bask, J. A. R. Griffith, O. Karban, J. M. Nelson, S. Roman, and G. Tungate, Nucl. Phys. A275, 381 (1977).

[6]F. Rybicki, T. Tamura, and G. R. Satchler, Nucl. Phys. A146, 659 (1970).

[7]C. R. Gould, D. P. Balamuth, P. F. Hinrichsen, and R. W. Zurmühle, Phys. Rev. 188, 1792 (1969).

[8]T. Hasegawa, N. Ueda, N. Kishida, H. Ohnuma, T. Fujisawa, T. Wada, K. Iwatani, T. Tanaka, and Y. Wakuta, in *Proceedings of the 1978 Institute for Nuclear Study International Symposium on Nuclear Direct Reaction Mechanism*, edited by M. Tanifuji and K. Yazaki (Institute for Nuclear Study, University of Tokyo, Tokyo, 1979), p. 105.

[9]M. Igarash, unpublished.

[10]N. Kishida and H. Ohnuma, J. Phys. Soc. Jpn. 46, 1375 (1979).

[11]R. V. Reid, Ann. Phys. (N.Y.) 50, 411 (1968).

[12]G. W. Greenlees and G. J. Pyle, Phys. Rev. 149, 836 (1966).

[13]F. T. Barker, S. Davis, C. Glashausser, and A. B. Robins, Nucl. Phys. A233, 409 (1974).

[14]R. C. Johnson and F. D. Santos, Part. Nucl. 2, 285 (1971).

[15]L. D. Knutson and W. Haeberli, Phys. Rev. Lett. 35, 558 (1975).

[16]C. M. Perey and F. G. Perey, Phys. Rev. 152, 923 (1966).

[17]F. D. Becchetti and G. W. Greenlees, Phys. Rev. 182, 1190 (1969).

[18]G. L. Wales and R. C. Johnson, Nucl. Phys. A274, 168 (1976).

[19]R. C. Johnson, Nucl. Phys. A90, 289 (1967); R. R. Cadmus, Jr. and W. Haeberli, Nucl. Phys. A327, 419 (1979); H. Ohnuma *et al.*, Phys. Lett. 97B, 192 (1980).

Selectivity in Two-Particle Exclusive Heavy-Ion Reactions

R. R. Betts, H.-G. Clerc,[(a)] B. B. Back, I. Ahmad, K. L. Wolf, and B. G. Glagola
Chemistry Division, Argonne National Laboratory, Argonne, Illinois 60439
(Received 25 September 1980)

A high-resolution study of two-particle exclusive reactions of ^{28}Si + ^{28}Si over a wide range of bombarding energy shows interesting selectivity in both the mass and the energy spectra. The mass spectra display an enhanced population of every fourth mass which gives way to an enhancement of every second mass at the higher energies. The energy spectrum of inelastically scattered particles shows a selective population of mutually excited yrast states in both fragments.

PACS numbers: 25.70.Bc, 25.70.Hi

There have been essentially no previous studies of heavy-ion reactions with projectiles heavier than ^{16}O in which the energy resolution was sufficient to resolve individual final states of the product nuclei.[1] Such experiments are potentially of great interest as they in principle contain significant information on the reaction mechanism through, for example, any selectivity in final-state population. Indications of such selectivity have been reported by Novotny *et al.*,[2] who observed broad structures in the spectrum of inelastically scattered ^{32}S from ^{28}Si. The energy resolution of the experiment precluded, however, any identification of these structures.

