(1980).
[5]C. K. Gelbke, M. Bini, C. Olmer, D. L. Hendrie, J. L. Laville, J. Mahoney, M. C. Mermaz, D. K. Scott, and H. H. Wieman, Phys. Lett. 71B, 83 (1977).
[6]H. W. Wittern, Phys. Lett. 32B, 441 (1970).
[7]A. S. Goldhaber and H. H. Heckman, Annu. Rev. Nucl. Sci. 28, 161 (1978).
[8]C. M. Castaneda, H. A. Smith, P. P. Singh, and H. Karwowski, Phys. Rev. C 21, 179 (1980).
[9]R. Shyam, G. Baur, F. Rösel, and D. Trautmann, Phys. Rev. C 19, 1246 (1979).
[10]A. Gamp, J. C. Jacmart, N. Poffe, H. Doubre, and J. C. Roynette, Phys. Lett. 74B, 215 (1978).
[11]J. L. Quebert, B. Frois, L. Marquez, G. Sousbie, R. Ost, K. Bethge, and G. Gruber, Phys. Rev. Lett. 32, 1136 (1974).

Nuclear-Shape Effects in the Inelastic Scattering of Polarized Deuterons at 56 MeV

K. Hatanaka
Research Center for Nuclear Physics, Osaka University, Suita, Osaka 565, Japan

and

M. Nakamura, K. Imai, T. Noro, H. Shimizu, H. Sakamoto, J. Shirai, T. Matsusue, and K. Nisimura
Department of Physics, Kyoto University, Kyoto 606, Japan
(Received 22 September 1980)

Differential cross sections and vector analyzing powers for the deuteron elastic and inelastic scattering from ^{24}Mg and ^{28}Si have been measured at 56 MeV. The coupled-channels analysis has been performed to obtain the simultaneous fits to the elastic- and inelastic-scattering data. The dependence of the coupled-channels calculations on the shape of nuclei has been investigated in comparison with the proton inelastic scattering.

PACS numbers: 25.50.Dt, 21.10.Ft, 24.70.+s

In recent years, there have been many studies for the determination of the shape of nuclei. It has been pointed out that the coupled-channels (CC) analysis of the elastic and inelastic scattering of polarized protons or deuterons is sensitive to the shape of nuclear deformation.[1-5] For a 0^+-2^+ rotational excitation, for example, there are two nuclear matrix elements: one between 0^+ and 2^+; another between two 2^+ functions. They are related to the $E2$ transition probability and quadrupole moments of the excited state, respectively. The sign of the quadrupole moment is related to the sign of the nuclear matrix element and will affect the results of the calculation.[6] A coupled-channels analysis of the proton inelastic scattering at 65 MeV was recently performed and it was found that the diffraction pattern of the angular dependence of the asymmetry showed shifts in different directions whether prolate or oblate static deformation was present.[7] The larger shifts were reported for the vector analyzing power of the deuteron elastic and inelastic scattering around 10 MeV.[8] Although the strong dependence of the deuteron scattering on the nuclear deformation has been suggested by some authors,[9,10] the experiments were concentrated at low energies. It is interesting to investigate this problem at higher energies where the reaction mechanism is considered to be direct and almost free from the compound nucleus effects. In this Letter we report the measurements and CC analysis of the deuteron inelastic scattering to the first 2^+ states of ^{24}Mg and ^{28}Si at 56 MeV.

The experiments were performed with 56 MeV vector polarized deuterons from the AVF cyclotron at the Research Center for Nuclear Physics, Osaka University. Polarized deuterons were produced by the atomic-beam–type ion source.[11] The beam current was 5–20 nA on target. The beam polarization was monitored continuously during the measurements by a ^{12}C polarimeter and was (70–80)% of the ideal value. The sign of the beam polarization was changed every second. The scattered deuterons were detected by a pair of counter telescopes placed at symmetric angles to the beam direction. Each telescope consisted of a 400-μm-thick transmission-type Si detector and a 15-mm-thick high-purity Ge detector cooled by liquid nitrogen. The particle identification was made with ΔE and E signals. The enriched ^{24}Mg and natural ^{28}Si targets were self-supporting metallic foils with thickness of about 3 mg/cm^2.

Figure 1 shows the angular distributions of the differential cross section, σ, and the vector analyzing power, iT_{11}, for the inelastic scattering to the first 2^+ states of ^{24}Mg and ^{28}Si. The error bars shown in the figure indicate the statistical uncertainties only. The angular distributions for the elastic scattering were also measured at the same time. The results of the elastic scattering have been reported elsewhere.[12] The uncertainties in the normalization of the analyzing power of the carbon polarimeter caused a normalization error of ± 10% in the analyzing-power measurements.[12] The absolute normalization of the differential cross section was estimated to be accurate to ± 10% because of the ambiguities of the target thickness and the beam integration. In Fig. 1, remarkable differences can be observed between angular distributions of iT_{11} for ^{24}Mg and ^{28}Si in the angular range of 25°–55°. These differences can be observed neither for the deuteron elastic scattering at 56 MeV nor for the proton inelastic scattering at 65 MeV.[13]

The dashed lines in Fig. 1 show the results of distorted-wave Born-approximation (DWBA) calculations describing the direct excitation of rotational states. The optical-model (OM) parameters were obtained from the simultaneous analysis of the elastic cross sections and vector analyzing powers. The search code MAGALI of Raynal was used. The final parameter values and the fits to the elastic-scattering data were reported in previous works.[12,14] The macroscopic DWBA calculations were obtained by assuming quadrupole deformations of all the potential terms. The β_2 values used for ^{24}Mg and ^{28}Si were 0.42 and 0.34, respectively, and they were consistent with the values previously obtained.[3,4] Although the σ was fairly well reproduced by DWBA, the fit to the iT_{11} was not good at forward angles.

It is well known that ^{24}Mg and ^{28}Si are characterized by large deformations. The analysis of the inelastic scattering data will be reasonably performed when the higher-order processes derived from the strong coupling among the rotational states are kept in consideration. A coupled-channels method is required; Raynal's computer program ECIS was used in this analysis. Calculations were performed with the simple $(0^+)_{K^\pi=0^+}$-$(2^+)_{K^\pi=0^+}$ coupling scheme by assuming an axially symmetric rigid deformation. The searches for OM parameters and deformations were performed to obtain the simultaneous fits to the elastic and inelastic cross sections and vector analyzing powers. The OM parameters were slightly changed from values obtained from the OM analysis of the elastic-scattering data. The hexadecapole deformation values were reported to be 0.05 ± 0.04 and 0.1 for ^{24}Mg and ^{28}Si, respectively.[4,15] The hexa-

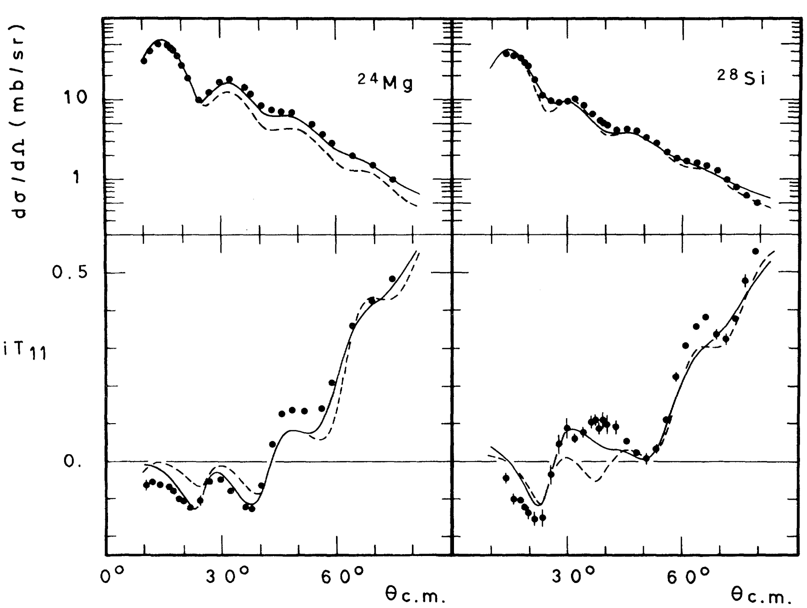

FIG. 1. Angular distributions of the differential cross sections and vector analyzing powers for the deuteron inelastic scattering to the first 2^+ states of ^{24}Mg and ^{28}Si. The solid and dashed lines represent the results of the CC and DWBA calculations, respectively.

decapole deformation was included only for ^{28}Si with a value of $\beta_4 = 0.1$ in all CC calculations. The solid curves in Fig. 1 correspond to the final results of the CC analysis if one assumes prolate deformation for ^{24}Mg, $\beta_2 = +0.40$, and oblate deformation for ^{28}Si, $\beta_2 = -0.31$. The signs of β_2 are consistent with previous works. The elastic cross sections and vector analyzing powers were well reproduced as well as by the OM analysis. As collective low-lying states of ^{24}Mg are grouped in the rotational bands built on the γ-vibrational state and on the ground state; the application of the rotational model to ^{24}Mg requires the asymmetric version.[16] A calculation with the value of $\gamma = 21°$, however, brought no significant improvement of the fits. It can be seen from Fig. 1 that both the cross sections and the vector analyzing powers were well reproduced by CC calculations and that the fit to the vector analyzing power for ^{28}Si was much improved in comparison with the DWBA calculation.

Figure 2 shows the prolate-oblate effect for the proton and deuteron inelastic scattering. The proton data were measured by Sakaguchi *et al.* at 65 MeV[13] and were analyzed with the same procedure as mentioned above. In the figure, the solid and dashed lines represent the results of CC calculations with the correct and the opposite sign of the quadrupole deformation, respectively. For both the proton and deuteron inelastic scattering, the diffraction pattern of the angular dependence of the calculated asymmetry shows shifts in different directions whether prolate or oblate static deformation is assumed. Besides the angular shifts another prolate-oblate effect is observed for the iT_{11} of the deuteron inelastic scattering over the angular range of 25°–55° (c.m.). This fact may be attributed to the surface absorption of deuterons by nuclei. The imaginary part of the OM potential is dominated by the volume type for 65 MeV protons.[17] On the other hand, deuterons are mainly absorbed at the nuclear surface even at 56 MeV. This is a reason why the deuteron scattering was more sensitive to the shape of nuclei than the proton scattering.

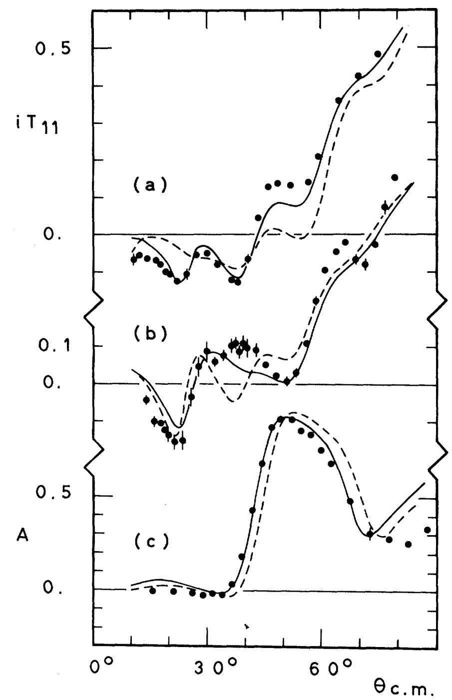

FIG. 2. Asymmetries for the inelastic scattering to the first 2^+ states: (a) iT_{11} for ^{24}Mg(d,d'), (b) iT_{11} for ^{28}Si(d,d'), and (c) A for ^{24}Mg(p,p'). The solid and dashed lines are CC predictions with the correct and the opposite sign of the deformation parameter, respectively.

In summary, the coupled-channels analysis of the elastic and inelastic scattering of polarized deuterons showed that the iT_{11} of the deuteron inelastic scattering at 56 MeV may be used to extract valuable structure informations. The reaction mechanism is considered to be direct and almost free from the compound-nucleus effects at this energy. In comparison with the proton inelastic scattering, the strong prolate-oblate effect in deuteron scattering is attributed to the surface absorption of deuterons by nuclei.

We wish to thank Professor M. Kondo for his continuous interest and encouragement throughout this work. We are also grateful to Professor S. Kobayashi for encouragement and many valuable comments. Many thanks are also due to the Research Center for Nuclear Physics staff and the cyclotron crew for their kind help.

[1] A. G. Blair *et al.*, Phys. Rev. C 1, 444 (1970).
[2] J. Eenmaa *et al.*, Nucl. Phys. A218, 125 (1974).
[3] R. De Leo *et al.*, Phys. Rev. C 19, 646 (1979).
[4] R. De Leo *et al.*, Phys. Rev. C 20, 13 (1980).
[5] H. Clement *et al.*, Phys. Rev. Lett. 45, 599 (1980).
[6] J. Raynal, in *Proceedings of the Fourth International Symposium on Polarization Phenomena in Nuclear Reactions, Zürich, 1975*, edited by W. Grüebler and V. König (Birkhauser-Verlag, Basel and Stuttgart, 1976), p. 271.
[7] M. Nakamura *et al.*, J. Phys. Soc. Jpn. Suppl. 44, 557 (1978).
[8] H. Clement *et al.*, J. Phys. Soc. Jpn. Suppl. 44, 570 (1978).

[9]R. C. Brown *et al.*, Nucl. Phys. A191, 663 (1972).
[10]R. C. Brown *et al.*, Nucl. Phys. A208, 589 (1973).
[11]K. Imai *et al.*, Research Center for Nuclear Physics, Osaka, Annual Report, 1978 (unpublished), p. 154.
[12]K. Hatanaka *et al.*, Nucl. Phys. A340, 93 (1980).
[13]H. Sakaguchi *et al.*, Fizika (Zagreb), Suppl. 10, 53 (1978).
[14]K. Hatanaka *et al.*, Research Center for Nuclear Physics, Osaka, Annual Report, 1978 (unpublished), p. 24.
[15]R. de Swiniarski *et al.*, Nucl. Phys. A261, 111 (1976).
[16]W. F. Hornyak, *Nuclear Structure* (Academic, New York, 1975), p. 399.
[17]H. Sakaguchi *et al.*, Research Center for Nuclear Physics, Osaka, Annual Report, 1978 (unpublished), p. 12.

Laser Resolution of Unpolarized-Electron Scattering Cross Sections into Spin-Conserved and Spin-Flip Components

Burke Ritchie
Sandia National Laboratories, Albuquerque, New Mexico 87185
(Received 25 August 1980)

The theory is presented for one-photon free-free absorption by electrons scattering from high-Z atoms. The absorption cross section provides sufficient information to resolve the unpolarized-electron total cross section, $|f(\theta)|^2+|g(\theta)|^2$, into its individual components for spin-nonflip, $|f(\theta)|^2$, and spin-flip, $|g(\theta)|^2$, scattering. The observation of a spin-polarization effect for a spin-independent process (free-free absorption) is analogous to the Fano effect for bound-free absorption.

PACS numbers: 34.80.-i, 32.90.+a, 34.90.+q

The experiments pioneered by Weingartshofer and co-workers[1,2] measure the absorption and stimulated emission of CO_2-laser (0.117 eV) radiation by a monoenergetic electron beam which simultaneously scatters from an atomic or molecular target gas. These experiments concern radiative processes ranging from one to four photons induced by a fairly intense (nearly 10^8 W cm^{-2}) laser. In the weak-field limit,[3] one-photon absorption can be described rigorously by the electric-dipole transition matrix element of first-order perturbation theory.[4] In the dipole-velocity form of the radiative interaction, the absorption cross section is given by

$$I_a=(2\pi)^{-1}10^7(\mathrm{erg/W\cdot s})(I\alpha/E_p^{\,2})a_0^{\,4}(m_e^{\,2}/\hbar^3)(k_f/k_i)\,|\langle\psi_{\vec{k}_f}^{\,(-)}(\vec{r})\,|\,\hat{\rho}\cdot(-i\nabla)\,|\,\psi_{\vec{k}_i}^{\,(+)}(\vec{r})\rangle|^2, \quad (1)$$

where I is the radiation intensity in watts per square centimeter, E_p is the photon energy in atomic units, $\vec{k}_i$ ($\vec{k}_f$) is the initial (final) electron momentum in a_0^{-1}, and $\hat{\rho}$ is a unit vector in the direction of polarization of the radiation. The conceptual simplicity of Eq. (1) suggests that the design of experiments in the one-photon limit may be advantageous from the standpoint of interesting spectroscopic applications. As an example, the leading contributions to absorption are given below for the case in which the wave functions are calculated for a potential having a spin-orbit component. Then each wave function (at either the initial or final energy and for either outgoing or incoming boundary conditions) describes a radiation-free situation in which waves are incident on a target in a single spin state and are scattered into a mixture of spin states.[5] It is clear that a dipole-absorption matrix element exists which is *nondiagonal* in wave functions whose *incident-wave* components have opposite spin polarization, even though the operator is spin independent. The potential which causes scattering into a mixture of spin states from a single incident spin state ensures this. In fact, when the matrix element is defined for wave functions whose incident waves are in the same spin state, its leading contributions are identified with a well-known result derived by Low[6] which depends on the elastic-scattering spin-nonflip amplitude. However, when the matrix element is defined for wave functions whose incident waves are in opposite spin states, then its leading contributions give a new result which depends on the spin-flip scattering amplitude and on the phases of the $m_l=+1$, $m_s=-\frac{1}{2}$ and $m_l=-1$, $m_s=+\frac{1}{2}$ scattered waves. This leads to an azimuthal-angle–dependent absorption cross section in which the relative contributions of the spin-non-

