of $f_{5/2}$ excitation contributes. Using the "equivalent wave function" given above, a value of $g = 1.3$ is calculated, in good agreement with the experimental value.

We wish to thank Professor L. Zamick for many stimulating discussions and particularly for the theoretical calculations of magnetic moments.

†Work supported in part by the National Science Foundation and Bell Telephone Laboratories.

*Associate of the Graduate Faculty, Rutgers, The State University, New Brunswick, N. J. 08903.

[1]S. Cochavi, D. B. Fossan, S. H. Henson, D. E. Alburger, and E. K. Warburton, Phys. Rev. C 2, 2241 (1970).

[2]T. Nomura, C. Gil, H. Saito, T. Yamazaki, and M. Ishihara, Phys. Rev. Lett. 25, 1342 (1970); H. Saito, T. Nomura, and T. Yamazaki, J. Phys. Soc. Jap. 30, 1252 (1971).

[3]R. Hensler, J. W. Tape, L. Guthman, N. Benczer-Koller, R. Van Bree, and Jack R. MacDonald, Bull. Amer. Phys. Soc. 15, 601 (1970).

[4]C. J. S. Chapman, J. M. Greogory, R. W. Hill, and M. W. Johns, Proc. Roy. Soc., Ser. A 262, 541 (1961).

[5]R. E. Sheriff and D. Williams, Phys. Rev. 82, 651 (1951).

[6]G. D. Sprouse and S. S. Hanna, *Hyperfine Structure and Nuclear Radiation* (North-Holland, Amsterdam, 1968), p. 761.

[7]L. Zamick, private communication, and Phys. Lett. 34B, 472 (1971).

[8]H. Noya, A. Arima, and H. Horie, Progr. Theor. Phys., Suppl. 8, 33 (1959).

Analyzing Power, Polarization, and Spin Flip in Inelastic Scattering at Isobaric Analog Resonances*

R. Boyd,† S. Davis, C. Glashausser, and C. F. Haynes
Rutgers, The State University, New Brunswick, New Jersey 08903

(Received 12 October 1971)

Measurement of the spin-flip probability with a polarized proton beam leads to a straightforward determination of both polarization (P) and analyzing power (A) in inelastic scattering at analog resonances. Calculations including direct-reaction background indicate that $P-A$ is insensitive to precise values of background parameters but quite sensitive to the configuration assumed for the analog state.

The analyzing power (A) in the inelastic scattering of protons from a 0^+ target nucleus at an isolated isobaric analog resonance (IAR) is exactly zero if there is no direct-reaction (DR) background; this was shown by Harney.[1] Thus a measurement of A at such a resonance gives no nuclear structure information, whereas a measurement of the polarization (P) of the inelastically scattered protons contains considerable information. Direct measurement of P, however, is very difficult since it requires a double scattering; no such measurements have been performed at an IAR. In fact, there is little experimental evidence for a difference between P and A in inelastic scattering.[2] It is the purpose of the present Letter (a) to note that both P and A can sometimes be determined by the measurement of the spin flip of a polarized beam, (b) to present analyzing-power data for inelastic scattering via an IAR to the 2_1^+ state of ^{88}Sr, and (c) to show calculations for the 2_1^+ state in ^{88}Sr and ^{124}Sn which indicate that the difference between P and A should be large and should provide a sensitive test of previously determined wave functions.[3,4]

The defining equations for P, A, the differential cross section $d\sigma/d\Omega$, and the spin-flip probability S are as follows:

$$\begin{aligned}\sigma(\theta)P(\theta) &= \sigma^{++}(\theta) + \sigma^{-+}(\theta) - \sigma^{+-}(\theta) - \sigma^{--}(\theta),\\ \sigma(\theta)A(\theta) &= \sigma^{++}(\theta) + \sigma^{+-}(\theta) - \sigma^{-+}(\theta) - \sigma^{--}(\theta),\\ \sigma(\theta)S(\theta) &= \sigma^{+-}(\theta) + \sigma^{-+}(\theta),\\ \sigma(\theta) &= \sigma^{++}(\theta) + \sigma^{+-}(\theta) + \sigma^{-+}(\theta) + \sigma^{--}(\theta)\\ &= 2d\sigma(\theta)/d\Omega.\end{aligned} \tag{1}$$

The z axis is chosen along the normal to the reaction plane, and $\sigma^{+-}(\theta)$, e.g., is the partial differential cross section for scattering from an incoming spin-up state (+) to a final spin-down state (−). The quantity $S(\theta)$ can be measured with an unpolarized beam by observing at 90° to the reaction plane the γ decay to the ground state (0^+) in coincidence with the inelastically scattered protons[5]; this method is suitable for excited states of spin 2^+ or 1^+. With a polarized beam such a measurement determines both $\sigma^{+-}(\theta)$ and

$\sigma^{-+}(\theta)$ individually. Measurement of A and $d\sigma/d\Omega$ at the same angle θ then completely determines $P(\theta)$.

In principle, one such measurement with proton counters at symmetric angles relative to the beam direction could determine all four independent quantities of Eq. (1). In practice, however, $d\sigma/d\Omega$ can be measured more reliably with an unpolarized beam, and both spin directions of the polarized beam should be used for the other measurements. With a beam of 20 nA or more of polarized protons, which is available at several laboratories, the measurement of σ^{+-} and σ^{-+} is not much more difficult than the measurement of S, since the unpolarized-beam intensity is usually limited by counting rate in the γ detector. With spin-flip cross sections of the order of 1 mb/sr, statistical errors of about ± 0.02 should be possible in a counting time of about 1 h. The necessity for good beam-energy definition and good overall energy resolution imposes strict limits on allowable target thicknesses and angular acceptances in a double-scattering measurement of P. Such an experiment seems possible only with the polarimeter in the focal plane of forthcoming very high-acceptance magnets; even then, the present method is more efficient.

We have measured A in inelastic scattering to the 1.84-MeV 2_1^+ state in ^{88}Sr at the 7.0, 7.08, and 7.53 MeV IAR in ^{89}Y. The data were taken with the Rutgers-Bell tandem and Lamb-shift polarized ion source.[6] Beam currents were normally 0.5–1 nA; targets of natural strontium were 0.5–1 mg/cm^2 thick. Data at the 7.53-MeV $\frac{3}{2}^+$ resonance are shown in Fig. 1 along with cross sections from Cosman, Joyce, and Shafroth[7] and theoretical curves described below. The ratio R of on-resonance to off-resonance cross section in ^{88}Sr is about 15:1; the same ratio for ^{124}Sn near the 10.65-MeV $\frac{7}{2}^-$ resonance in ^{125}Sb is about 5:1. Data for the latter reaction reported by Arking *et al.*[4] are shown in Fig. 2. Note that the difference in the analyzing powers in the two cases reflects at least in part the difference in the ratio R for the two nuclei; this is consistent with Harney's theorem.[1]

Calculations of the four independent quantities of Eq. (1) have been carried out with the distorted-wave Born approximation (DWBA) code DWUCK[8] modified[4] to include the effect of an IAR. The calculations for ^{88}Sr (Fig. 1) are preliminary in the sense that no attempt has yet been made to systematically vary the inelastic decay widths $\Gamma_{p'L_pJ_p}$ to obtain a fit to $d\sigma/d\Omega$ and A. The wave

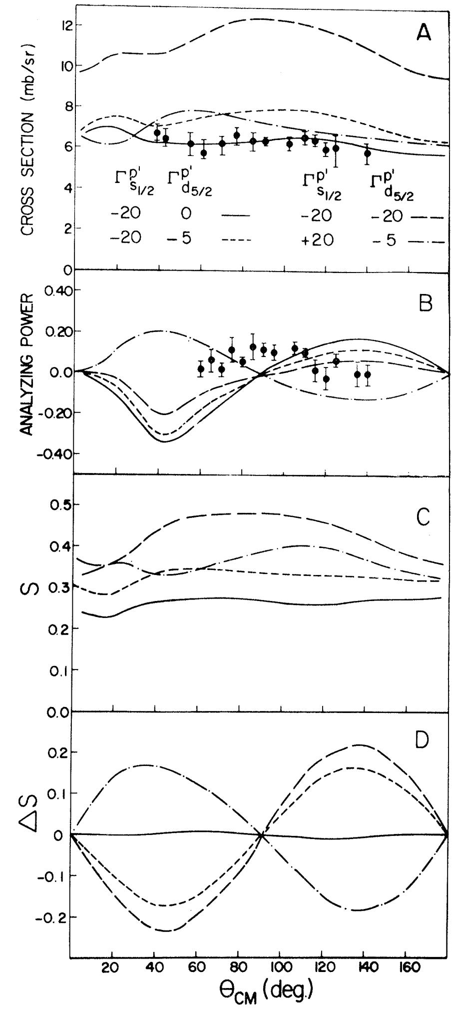

FIG. 1. Angular distributions for ^{88}Sr at the 7.53-MeV $\frac{3}{2}^+$ resonance in ^{89}Y. The experimental cross section is from Ref. 7. All the curves were calculated with a value of β of 0.11; the values of the partial widths are given in keV.

function obtained by Spencer *et al.*[3] indicates that the IAR decays predominantly via $3s_{1/2}$ and $2d_{5/2}$ waves, with small admixtures of $2d_{3/2}$ and $1g_{7/2}$ waves. The value of the deformation parameter β which determines the magnitude of the DR background was found to be 0.11 in inelastic proton scattering at 19 MeV[9]; it is 0.14 in the tabulation of Stelson and Grodzins.[10] The real and imaginary parts of the central optical potential were deformed and Coulomb excitation was included.

The inelastic widths used in the calculations for ^{124}Sn were determined by Arking *et al.*[4] by fitting their inelastic cross-section and analyzing-power data; all other parameters are also as de-

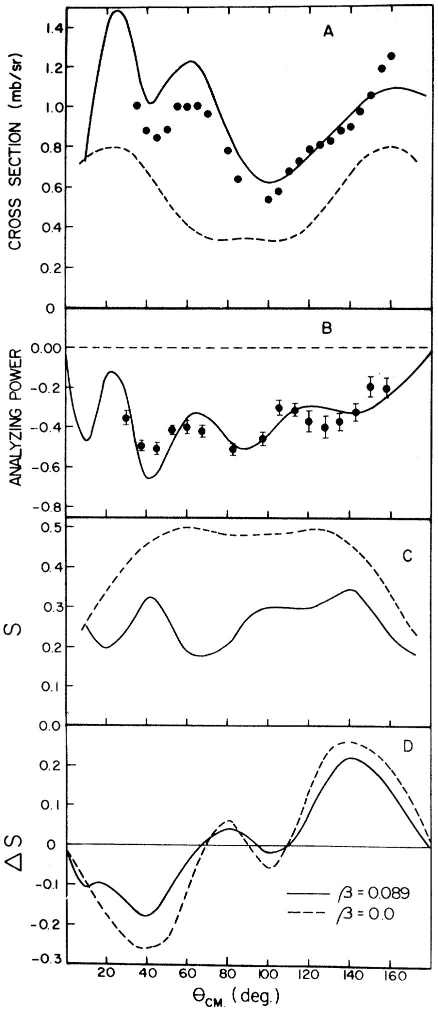

FIG. 2. Angular distributions for ^{124}Sn at the 10.65-MeV $\frac{7}{2}^-$ resonance in ^{125}Sb. The experimental data and the parameters for the calculated curves are taken from Ref. 4.

termined in their analysis. Their calculations of $d\sigma/d\Omega$ and A are shown in Fig. 2. The results of the present calculations of S and ΔS [$\Delta S = (\sigma^{+-} - \sigma^{-+})/\sigma = 0.5\,(A-P)$] are also shown in Fig. 2; the curves for a β of 0.089 are thus predictions. The measurement of S and ΔS would serve as a test of both the wave function derived in Ref. 4 and the reaction mechanism assumed.

The calculations are interesting in several respects. For an isolated resonance of definite parity, it can be shown that $\sigma^{+-}(\theta) = \sigma^{-+}(\pi-\theta)$ and $\sigma^{++}(\theta) = \sigma^{--}(\pi-\theta)$, so that $P(\theta) = -P(\pi-\theta)$ and $P(\pi/2) = 0 = A$. This determines the approximate symmetries apparent in the calculated curves; the deviations from these relations are an indication of DR background.

The curves shown in Fig. 1 illustrate the effects of changing the magnitudes and relative signs of the decay amplitudes for ^{88}Sr. Only $3s_{1/2}$ and $2d_{5/2}$ waves are considered in order to isolate the effects of various changes. The calculations indicate that the four independent measurements are remarkably complementary. The prediction of ΔS is very sensitive to a small admixture of the $d_{5/2}$ wave, but less sensitive to the change from a small admixture to a large admixture. In addition, ΔS depends critically on the relative sign of the s and d waves, but not on the absolute value of either. The cross section is rahter insensitive to a small admixture of the d wave, but increases dramatically with a large admixture; it is only slightly affected by changes in the signs of the amplitudes. The predicted analyzing power is quite small and does not agree with the data, so that some $d_{3/2}$ or $g_{7/2}$ components should probably be introduced into a more realistic calculation. However, even though A is small, its sign depends only on the absolute sign of the $s_{1/2}$ component; it is independent of the sign of the $d_{5/2}$ component. Finally, S is not a rapidly varying function of any of these variables, but still changes noticeably as all of these parameters vary.

The parameter β and the optical parameters which describe the DR background can normally be determined by fitting off-resonance data. The values derived are subject to uncertainties which can affect spectroscopic results derived from the on-resonance data. However, ΔS seems insensitive to β over a wide range, while $d\sigma/d\Omega$, A, P, and S all change markedly with β. This is illustrated in Fig. 2 for ^{124}Sn, where the two sets of curves correspond to calculations with no DR background ($\beta = 0.0$) and background which fits the off-resonance data ($\beta = 0.089$). The unique behavior of ΔS is even more striking for ^{88}Sr; the curves shown in Fig. 1(d) are hardly affected as β is varied between 0.0 and 0.20. This insensitivity of ΔS to β should be important for spectroscopy; it means, e.g., that ΔS is little affected by uncertainties in optical parameters. It also means that even when the DR background is a large percentage of the cross section, as in ^{124}Sn, large differences between P and A can still be observed. (In a purely direct reaction, $P-A$ is expected to be almost zero unless the interference between the amplitudes for spin transfer equal to 0 and 1 is anomalously large.[11])

A measurement of S (with an unpolarized beam) corresponds to just one of the many in-plane and out-of-plane correlations used by Abramson *et al.*[12] to determine wave functions in the cadmium isotopes. No calculations of these other correlations with both nuclear and Coulomb DR background or with a polarized beam have yet been performed. However, the correlation discussed here, which for 1^+ and 2^+ states is related to the spin-flip probability, it not necessarily more significant than the others in the determination of nuclear wave functions. Thus measurements of these other correlations should also be undertaken with a polarized beam, and they should not be limited to residual states of spin 1^+ and 2^+. Abramson *et al.* note, however, that a large incoherent compound-nucleus background was the largest source of error in their analysis. This problem can be avoided in the analysis of P and A measurements since the products $A\,d\sigma/d\Omega$ and $P\,d\sigma/d\Omega$ have no contributions from incoherent compound-nucleus reactions.[13]

It has previously been shown that polarized beams are useful in the study of IAR if the direct-reaction background is large.[14,4] Here we have shown that they should be important even if this background is small or nonexistent since they can be used to measure P. Further, our calculations indicate that large differences can be expected between P and A even with a large direct background provided there is sufficient exit-channel interference between waves with orbital angular momenta; it is therefore useful to measure both A and P. Thus polarized-beam studies of the particular p-γ correlation discussed here, and very likely of many other such correlations, should prove important in the study of both wave functions and reaction mechanisms for IAR.

We are grateful to R. Arking, Dr. G. Graw, and Dr. S. Yoshida for helpful conversations.

*Work supported in part by the National Science Foundation.

†Present address: Varian Physics Building, Stanford University, Stanford, Calif. 94305.

[1]H. L. Harney, Phys. Lett. 28B, 249 (1968).

[2]M. Ahmed, J. Lowe, P. M. Rolph, and V. Hnizdo, University of Birmingham Report No. 71-10 (unpublished). These authors present data for $^{12}C(\vec{p},p'\gamma)$ at 30 MeV with the geometry described below. We interpret these data to indicate some difference between P and A, but the errors are quite large.

[3]J. E. Spencer, E. R. Cosman, H. A. Enge, and A. K. Kerman, Phys. Rev. C 3, 1179 (1971).

[4]R. Arking, R. N. Boyd, J. C. Lombardi, A. B. Robbins, and S. Yoshida, Phys. Rev. Lett. 27, 1396 (1971).

[5]F. H. Schmidt, R. E. Brown, J. B. Gerhart, and W. A. Kolasinski, Nucl. Phys. 52, 353 (1964).

[6]R. N. Boyd, J. C. Lombardi, A. B. Robbins, and D. E. Schecter, Nucl. Instrum. Methods 81, 149 (1970).

[7]E. R. Cosman, J. Joyce, and S. M. Shafroth, Nucl. Phys. A108, 519 (1967).

[8]P. D. Kunz, DWUCK, a computer code for DWBA calculations, University of Colorado, 1969 (unpublished).

[9]M. M. Stautberg, J. J. Kraushaar, and B. W. Ridley, Phys. Rev. 157, 977 (1967).

[10]P. H. Stelson and L. Grodzins, Nucl. Data 1, 21 (1965).

[11]G. R. Satchler, Phys. Lett. 19, 312 (1965).

[12]E. Abramson, R. A. Eisenstein, I. Plesser, Z. Vager, and J. P. Wurm, Nucl. Phys. A144, 321 (1970).

[13]W. J. Thompson, Phys. Lett. 25B, 454 (1967).

[14]H. Clement, G. Graw, W. Kretschmer, and P. Schulze-Döbold, Phys. Rev. Lett. 27, 526 (1971).

Mössbauer Experiments on ^{180}Hf and the Structure of the 8^- Two-Quasiparticle State*

H. J. Körner,† F. E. Wagner,† and B. D. Dunlap
Argonne National Laboratory, Argonne, Illinois 60439
(Received 11 October 1971)

The magnetic moment of the 1142-keV 8^- state of ^{180}Hf was deduced from the known hyperfine splitting of the isomeric state in $(Hf_{0.1}Zr_{0.9})Fe_2$ and the hyperfine field in this compound. This field $H_{hf} = -200 \pm 20$ kOe was obtained from Mössbauer experiments with the 93.3-keV γ rays of ^{180}Hf. The deduced result $\mu(8^-) = +(8.6 \pm 1.0)\mu_N$ identifies the 8^- state as a virtually pure two-proton configuration.

Krane *et al.*[1] recently determined the parity-nonconserving forward-backward asymmetry of the 501-keV γ rays emitted by ^{180m}Hf nuclei polarized at low temperatures. Making use of the hyperfine field in the ferromagnetic cubic Laves-phase compound $(Hf_{0.1}Zr_{0.9})Fe_2$ and cooling to 0.021 K, they obtained a nuclear polarization of 72%. The corresponding magnetic hyperfine splitting of the 1142-keV state is $\Delta(8^-) = \mu(8^-)H_{hf}/I\mu_N = -(6.81 \pm 0.43)\times 10^{-7}$ eV. We have measured the hyperfine field H_{hf} in $(Hf_{0.1}Zr_{0.9})Fe_2$ by means of Mössbauer experiments on the first excited 2^+