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Observation of Polarization-Analyzing Power Inequality in the Reaction ^{88}Sr$(p,p'\gamma)^{88}$Sr Using Polarized Protons*

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(Received 1 August 1972)

The difference between the polarization and the analyzing power in the inelastic scattering of protons at isobaric analog resonances in ^{89}Y has been determined by measuring the spin-flip probability of a polarized beam. The differences are large, and are sensitive to the structure of the resonances.

In a recent Letter[1] it was suggested that spin-flip measurements with a polarized incident proton beam be used to determine the difference between the polarization (p_z) and the analyzing power (A_z) for inelastic scattering at isobaric analog resonances (IAR's). Here we present the first results of such measurements.

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

$$\begin{aligned} d\sigma(\theta)/d\Omega &= \tfrac{1}{2}(\sigma^{++}+\sigma^{+-}+\sigma^{-+}+\sigma^{--}) \equiv \tfrac{1}{2}\sigma(\theta), \\ p_z(\theta)\sigma(\theta) &= \sigma^{++}+\sigma^{-+}-\sigma^{+-}-\sigma^{--}, \\ A_z(\theta)\sigma(\theta) &= \sigma^{++}+\sigma^{+-}-\sigma^{-+}-\sigma^{--}, \\ S(\theta)\sigma(\theta) &= \sigma^{+-}+\sigma^{-+}, \\ \Delta S(\theta)\sigma(\theta) &= \sigma^{+-}-\sigma^{-+} = \tfrac{1}{2}(A_z - p_z)\sigma(\theta). \end{aligned} \qquad (1)$$

The z axis is chosen along the direction $\hat{k}_{\text{in}}\times\hat{k}_{\text{out}}$, where $\hat{k}_{\text{in}}$ and $\hat{k}_{\text{out}}$ are the incident and outgoing proton directions.[2] Then $\sigma^{+-}(\theta)$, for instance, is the partial differential cross section for scattering from a state with incident proton spin in the positive z direction to a final state with outgoing proton spin in the negative z direction. Only four of the five quantities defined above are independent, since there are only four incoherent partial cross sections. For elastic scattering, time-reversal invariance requires that p_z and A_z be equal. No such requirement exists for inelastic scattering, but until now there has been little experimental evidence for a difference between p_z and A_z.[3] Differences occur if the cross section for spin flip from + to − is different from the cross section for spin flip from − to +.

In the present experiment we have measured $A_z(\theta)$, $S(\theta)$, and $\Delta S(\theta)/S(\theta)$ for inelastic scattering to the 1.84-MeV $2_1{}^+$ state of ^{88}Sr at three resonances: those at 7.00 MeV ($\frac{5}{2}^+$), 7.08 MeV ($\frac{3}{2}^+$), and 7.53 MeV ($\frac{3}{2}^+$) incident proton energy. The differential cross sections had been measured previously[4] for the two lower-energy resonances, and we measured that for the 7.53-MeV resonance. Our measurements were performed using the polarized proton beams[5] of the tandem Van de Graaff accelerators at both Rutgers University and Stanford University. Targets were natural or enriched ^{88}Sr with thicknesses from 0.3 to 1.0 mg/cm^2. Proton counters [Si(Li) detectors] were set at symmetric angles on the right and left sides of the incident beam in the scattering plane. A NaI γ detector was placed above or below the scattering chamber along the z axis; it subtended a half-angle of about 11°. Coincidences between protons exciting the 1.84-MeV state in ^{88}Sr and the subsequent 1.84-MeV de-excitation γ rays were observed with a time-to-amplitude converter. With polarized beam currents of about 10 nA, ΔS measurements averaged about 10 h per angle.

The geometry chosen for the γ counter ensures that a true proton-γ coincidence corresponds to spin flip of the incident proton.[6] Thus, for a given sign of the polarization of the incident beam (parallel or antiparallel to the positive z axis), the quantity $\Delta S/S$ is proportional to the left-right asymmetry in the number of *proton-γ coincidences;* its measured value does not depend on the efficiency of the γ counter. Measurements of $\Delta S/S$ were taken with both spin-up (+) and spin-down (−) incident polarized beams to eliminate some sources of error; its value was thus calculated from the formula

$$\frac{\Delta S}{S}=\frac{1}{|p_B|}\frac{(M_L{}^+M_R{}^-/M_R{}^+M_L{}^-)^{1/2}-1}{(M_L{}^+M_R{}^-/M_R{}^+M_L{}^-)^{1/2}+1}, \qquad (2)$$

where $M_L{}^+$, for instance, is the number of coincidences between the left (L) particle detector and the γ counter with a spin-up incident beam. The beam polarization p_B was measured several times during each run and remained constant within about ±0.02. The analyzing power A_z is proportional to the left-right asymmetry in the proton singles counting rate. It is calculated like $\Delta S/S$, but with the substitution of proton singles counts for proton-γ coincidences in Eq. (2). The spin-flip probability S is proportional to the sum of the γ-ray coincidences from the left-right pair of proton detectors. It is independent of the sign of the polarization of the beam and was generally measured separately with an unpolarized beam to obtain better statistics. The absolute values of S and ΔS depend on the efficiency of the γ detector. This was determined using calibrated sources of γ rays with energies close to 1.84 MeV. The absolute value of S is accurate to about ±0.05.

Data taken at the 7.00-, 7.08-, and 7.53-MeV resonances in ^{89}Y are illustrated in Figs. 1(a), 1(b), and 1(c); the curves are discussed below. The first four sets of data in each figure are directly measured quantities. The fifth data set illustrates the difference between A_z and p_z; the values of p_z are derived from the measured values of A_z, $\Delta S/S$, and S. The values of S and $\Delta S/S$ have been corrected approximately for spin-nonflip contributions due to off-axis γ rays; this correction is about 0.02.

The most interesting feature of these data is the definite nonzero value of ΔS at all three resonances: p_z and A_z are different. The magnitudes and angular distributions of these differences are qualitatively similar to the estimates of Ref. 1. Note also that, as predicted,[1] the angular distributions of all the measured parameters appear characteristic of the resonances, so that each yields information about the wave function of the analog state. For example, the angular distribution of $\Delta S/S$ for the 7.08-MeV ($\frac{3}{2}^+$) resonance is very different from the angular distribution of $\Delta S/S$ for the 7.53-MeV ($\frac{3}{2}^+$) resonance; for the latter p_z is larger than A_z whereas for the former A_z is generally larger than p_z. The smaller quantity is close to zero at both resonances. Since Harney has shown that A_z depends on entrance channel interference and p_z depends on exit channel interference,[7] these data can be qualitatively interpreted to indicate that there is little interference between direct and compound-nucleus reactions at the 7.53-MeV resonance and that little interference exists between the exit-channel partial waves in the decay of the 7.08-MeV resonance.

These data are being analyzed quantitatively using the formalism of Arking *et al.*[8] in which direct-reaction and compound-nucleus resonance collision functions are added coherently. The parent state is described by the weak coupling of single-particle neutron orbitals of angular momentum quantum numbers l and j to the $0_1{}^+$ and $2_1{}^+$ states of ^{88}Sr. The decay amplitudes and signs of the corresponding fragments of the analog wave function are characterized by the proton partial widths $\Gamma_{lj}{}^{p'}$ and associated signs. A modified version of the distorted-wave Born-approximation code DWUCK[9] is being used for the calculations. Optical parameters of Ellis and Haeberli[10] were used in calculating the direct-reaction collision function. The value of the deformation parameter β which determines the direct-reaction background was chosen to be 0.11 on the basis of inelastic proton scattering at 19 MeV.[11] These parameters provide fair fits to angular distributions of $d\sigma(\theta)/d\Omega$ and $A_z(\theta)$ for inelastic scattering off resonance at 7.30 MeV.

In order to determine the wave functions of the resonances, the magnitudes and associated signs of the decay widths for all possible contributing total angular momenta should be varied until a good fit is obtained to all the measured data. This extensive search has not yet been performed. Preliminary calculations were made using inelastic widths based on the ^{89}Sr particle-phonon model wave functions of Spencer *et al.*[4] The relative signs associated with the partial widths were chosen to best represent the $\Delta S/S$ and A_z data which are very sensitive to these signs.[1] The total resonance widths and proton elastic widths of Ellis and Haeberli[10] were used in these calcu-

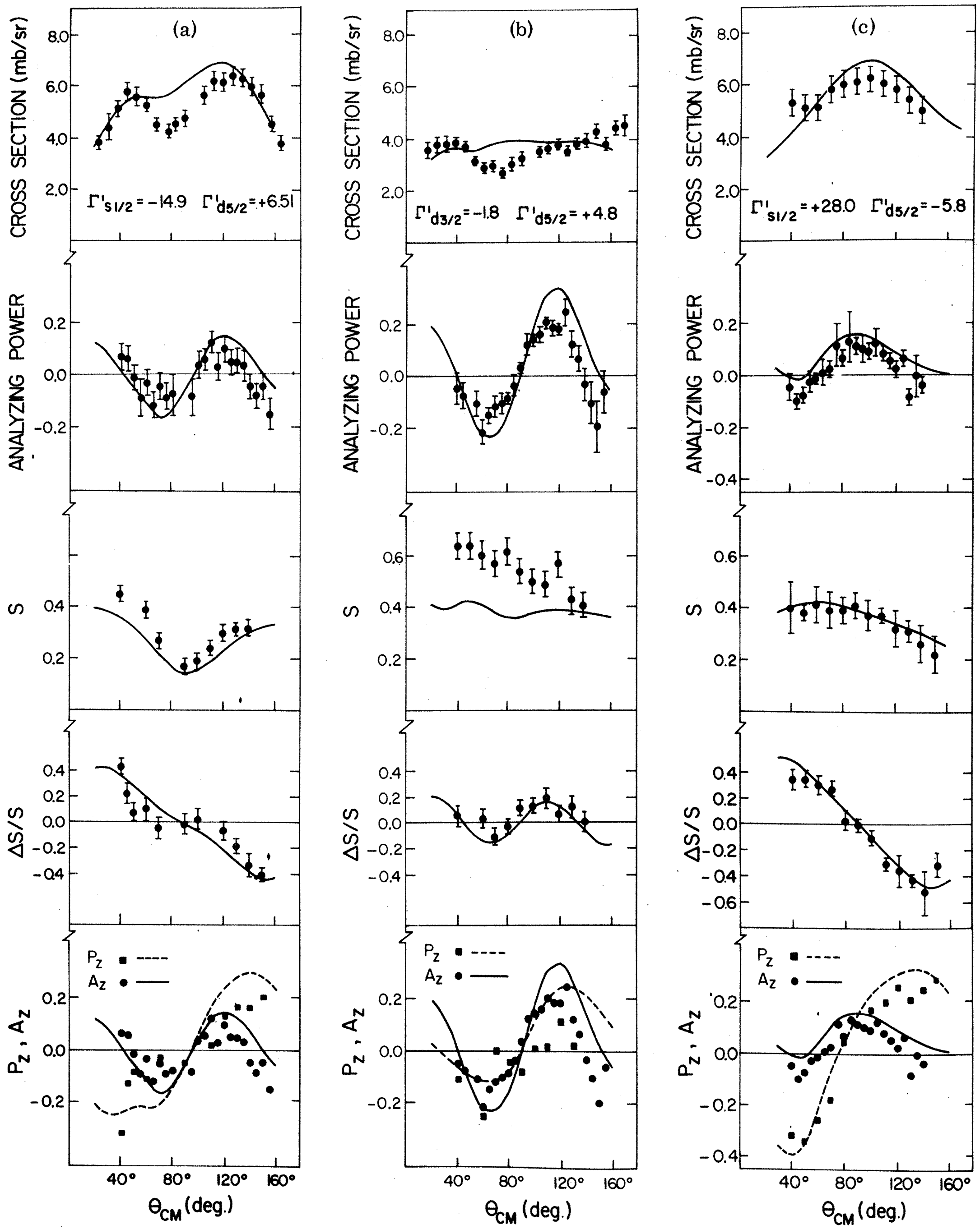

FIG. 1. Measured angular distributions of the quantities defined in Eq. (1) for inelastic scattering at the (a) 7.00-MeV, (b) 7.08-MeV, and (c) 7.53-MeV resonances in ^{89}Y. The $d\sigma/d\Omega$ measurements in (a) and (b) are from Ref. 4. The calculated curves are described in the text. Partial widths are expressed in keV.

lations. The results are shown as the curves in the figures; partial widths are given in keV. Qualitative agreement with the magnitudes and angular distributions of much of the data is good, although some difficulties are apparent. The cross section is generally not yet well described; the values of $S(\theta)$ at the 7.08-MeV resonance are fitted poorly. Still, these preliminary calculations are encouraging and they indicate the sensitivity of the measurements to the wave functions of the analog states. Note, for instance, that the large differences in the $\Delta S/S$ angular distributions between the two $\frac{3}{2}^+$ resonances at 7.08 and 7.53 MeV are explained by the very different values of the widths $\Gamma_{lj}{}^{p'}$ for the two resonances.

These results indicate that spin-flip measurements with polarized proton beams yield valuable information about IAR states and their parents. They provide conclusive evidence for the first time that p_z and A_z are generally different. The complementary information from p_z and A_z means that both are important spectroscopically. The method of measurement suggested in Ref. 1 and used here successfully for measurements at IAR's may also be extended to direct $(p, p'\gamma)$ reactions using polarized protons and ultimately to other direct reactions such as $(p, {}^3\mathrm{He}\gamma)$ (with polarized protons).

*Work supported in part by the National Science Foundation.

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α Decay of Neutron-Deficient Isotopes of Bismuth and Lead Produced in (Ar, xn) and (Kr, xn) Reactions

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(Received 10 July 1972)

Neutron-deficient isotopes of bismuth and lead have been produced in various heavy-ion-induced reactions. Argon and krypton ions were used as projectiles on ^{159}Tb, ^{155}Gd, and ^{109}Ag. We observed α emission from bismuth nuclides and isomers with $A=190-197$ and from lead isotopes with $A=186-190$. We give results on mass assignments, α-decay energies, half-lives, and α branching ratios. Two new lead isotopes were found: ^{187}Pb, $E_\alpha=6.08$ MeV, $t_{1/2}=17.5$ sec; and ^{186}Pb, $E_\alpha=6.32$ MeV, $t_{1/2}=7.9$ sec. No α-emitting isotopes of thallium were found, and upper limits significantly below 1% can be set on the α branching ratios of Tl isotopes with $A=182-187$.

The properties of neutron-deficient α emitters of bismuth and lead are not well known. The information listed in a recent compilation[1] or in the latest nuclide charts is based mostly on unpublished reports,[2-4] and details of the basis of the mass assignments are not available. We have investigated the production and decay of these nuclides in a variety of reactions.[5] We have confirmed the validity of most of the previous assignments but have found several discrepancies in the details of the decay properties. Two new lead isotopes, ^{186}Pb and ^{187}Pb, have been found, and