

## High-Spin-State Spectroscopy with the Reaction $^{88}\text{Sr}(p_{\text{pol}}, \pi^-)^{89}\text{Zr}$

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The pronounced selectivity of near-threshold  $(p, \pi^-)$  reactions for high-spin two-particle, one-hole states is exploited, in the first spectroscopic application of a  $(p, \pi^-)$  reaction, to identify previously unknown  $25/2^+$  and  $21/2^+$  ( $g_{9/2}$ )<sup>3</sup> states in  $^{89}\text{Zr}$ . Relative cross sections for the two transitions are well reproduced by simple model calculations. The analyzing power for the  $25/2^+$  state is markedly similar to previous  $(p_{\text{pol}}, \pi^-)$  results for two-particle, one-hole stretched states in lighter nuclei.

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A dramatic selectivity for certain discrete final states at low excitation has been observed recently<sup>1</sup> in exclusive  $(p, \pi^-)$  reactions induced on many nuclei, especially those (e.g.,  $^{48}\text{Ca}$ ) which have a high-spin  $j_> (= l + 1/2)$  neutron orbital filled and the corresponding proton orbital empty. The most strongly excited states were interpreted<sup>1,2</sup> as two-particle (protons), one-hole (neutron) configurations with maximal (or nearly maximal) angular momentum coupling, giving rise to so-called "stretched" (or nearly stretched) states. Such states are of interest because they should be relatively pure from a shell-model viewpoint and are among the simplest nuclear excitations at momentum transfers in excess of 500 MeV/c, a region where the momentum must be shared among at least three nucleons if no one of them is to carry much more than the Fermi momentum. Their selective population is favored by the large (linear and angular) momentum mismatch characteristic of exclusive  $(p, \pi^-)$  reactions, and by the assumed dominance in the reaction mechanism of two-nucleon processes— $p + n \rightarrow p + p + \pi^-$ —in which the proton interacts with a target neutron residing in a particular shell-model orbital. This interpretation in terms of a two-nucleon mechanism is supported by the excellent agreement between observed  $(p, \pi^-)$  spectra (acquired at a single angle)

for nuclei in the  $f_{7/2}$ -shell region ( $A = 42-54$ ) and simplified model calculations carried out recently by Brown, Scholten, and Toki.<sup>3</sup> The calculations employed shell-model excitation energies and structure amplitudes for pure  $(1f_{7/2})^n$  states populated in a zero-range, plane-wave-Born-approximation reaction treatment, combining two-proton stripping and single-neutron pickup.

The observed selectivity and the success of this simple treatment serve both to advance our understanding of the mechanism for producing or absorbing pions in nuclei, and to suggest spectroscopic applications of the  $(p, \pi^-)$  reaction.<sup>2</sup> In the present Letter we report results of an investigation of the reaction  $^{88}\text{Sr}(p, \pi^-)^{89}\text{Zr}$ , aimed at testing predictions of the model of Brown, Scholten, and Toki<sup>3</sup> in a different mass region, and at identifying previously unknown high-spin states in the  $g_{9/2}$  shell. The present measurements were made with considerably better energy resolution than those of Ref. 1, allowing extraction of cross-section and analyzing-power angular distributions for states of different spin within the same multiplet.

The identification of levels in  $^{89}\text{Zr}$  in this work is based upon comparison of measurements with calculated spectra and angular distributions. It is thus important to review briefly some components of the model<sup>3</sup> and independent experimental evidence

supporting its applicability for identifying high-spin states in the previously studied  $f_{7/2}$ -shell region. By construction, the model treats population only of states of two-particle, one-hole  $[(\pi lj)^2(\nu lj)^{-1}]$  configurations within the valence orbital. The selectivity for high-spin states in the calculated spectra arises predominantly from angular momentum matching and coupling considerations. The coupling possibilities are restricted by assuming, for a spin-zero target nucleus, that the spin ( $J$ ) and parity  $[P = (-1)^L]$  of a given final state are related to the total orbital angular momentum transfer  $L$  for the transition by  $P = (-1)^L$  and  $J = L \pm \frac{1}{2}$ . The latter constraint is imposed by the zero-range assumption, which requires the two final-state protons to be in a relative  $s$ -wave spin-singlet state, disallowing a spin transfer of  $S = \frac{3}{2}$  in the reaction. Final states with  $J = L - \frac{1}{2}$  are generally strongly suppressed by the  $9$ - $j$  coefficients connecting the  $jj$  and  $LS$  coupling schemes. Favored  $L$  values are determined from the reaction kinematics (characterized by linear momentum transfers typically in the range  $q \approx 500$ – $700$  MeV/ $c$ ) and the assumption that the reaction probability peaks in the nuclear surface region. The surface peaking is artificially enhanced by introducing a lower cutoff  $R_0$  on the radial overlap integral (presumably to simulate crudely the distortion effects of pion absorption), giving rise to  $L$ -dependent angular distributions dominated by the Bessel functions  $|j_L(qr)|^2$ , smeared over a small range of  $r$  in the surface region.

The net result of the above angular momentum considerations is that the calculated  $(p, \pi^-)$  spectra are typically dominated by two transitions with  $J = L + \frac{1}{2}$ , one to the stretched state with  $L = 3l$  and one with  $L = 3l - 2$ . For example, model calculations<sup>3</sup> yield  $^{48}\text{Ca}(p, \pi^-)^{49}\text{Ti}$  spectra dominated by the stretched  $(f_{7/2})^3$   $19/2^-$  state at  $E_x = 4.43$  MeV and by the second  $15/2^-$  state of this configuration at  $E_x = 3.76$  MeV. The observed spectra<sup>4</sup> for this case show two prominent peaks, at  $E_x = 4.4$  and  $4.0$  MeV, in very good agreement with the calculated excitation energies. Furthermore, the two observed peaks have quite different cross-section angular-distribution shapes, qualitatively consistent with expectations for the predicted  $L = 9$  and  $L = 7$  transitions,<sup>2</sup> and best reproduced by the calculations<sup>3</sup> when the cutoff radius  $R_0$  is adjusted to  $3.3$  ( $= 0.9A^{1/3}$ ) fm. The association of the observed peaks with the predicted  $15/2^-$  and  $19/2^-$  states is supported by independent spectroscopic studies of  $^{49}\text{Ti}$  via the reactions  $^{48}\text{Ca}(\alpha, 3n\gamma)$  (Behor *et al.*<sup>5</sup>) and  $^{51}\text{V}(d_{\text{pol}}, \alpha)$  (Nann *et al.*<sup>6</sup>). The former identi-

fies  $19/2^-$ ,  $17/2^-$ , and  $15/2^-$  yrast states at  $E_x = 4.38$ ,  $3.29$ , and  $2.51$  MeV, respectively, but does not provide evidence for a higher-lying  $15/2^-$  state.<sup>5</sup> The  $(d_{\text{pol}}, \alpha)$  results<sup>6</sup> at  $T_d = 80$  MeV indicate strong  $L = 6$ ,  $J = 7$  transitions to high-spin  $(f_{7/2})^3$  states at  $E_x = 3.29$ ,  $3.96$ , and  $4.38$  MeV. The  $17/2^-$  state at  $E_x = 3.29$  MeV is excited in the reaction  $^{48}\text{Ca}(p, \pi^-)$  as well, but only very weakly, as expected from the  $J = L - \frac{1}{2}$  suppression discussed above.

Given this success in accounting for observations in the calcium region, it is desirable to test predictions for  $(p, \pi^-)$  results involving nucleons in the next available  $(1g_{9/2})$   $j_>$  shell-model orbital. For this purpose, calculations have been carried out for  $^{88}\text{Sr}(p, \pi^-)^{89}\text{Sr}$  using  $(g_{9/2})^n$  shell-model wave functions given by Serduke, Lawson, and Gloeckner,<sup>7</sup> and fixing the cutoff radius  $R_0$  to the same value ( $0.9A^{1/3}$  fm) employed in the  $f_{7/2}$ -shell region. The predictions are compared in Figs. 1 and 2 with measurements performed (of typical polarization  $\sim 0.70$ ) at the Indiana University Cyclotron Facility with a polarized proton beam and a quadrupole-quadrupole-split-pole magnetic spectrometer optimized for low-energy pion detection. The focal plane detectors and electronics are described in detail elsewhere.<sup>8</sup> The pions were detected with an overall energy resolution of

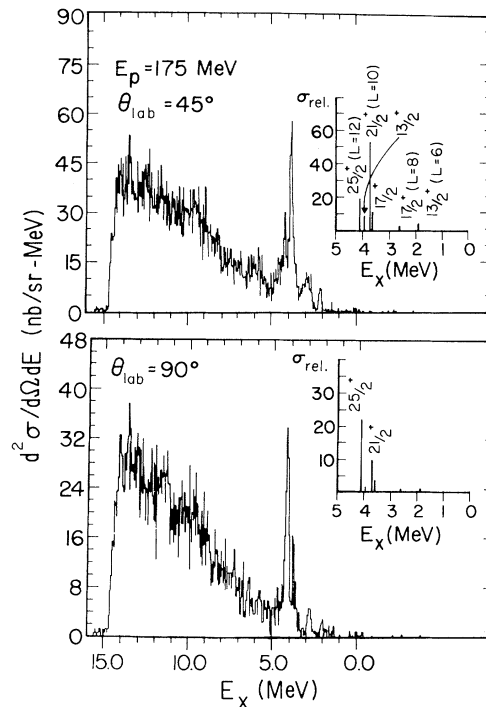


FIG. 1. Spectra for  $^{88}\text{Sr}(p, \pi^-)^{89}\text{Zr}$  at two angles compared with predictions (insets) discussed in text.

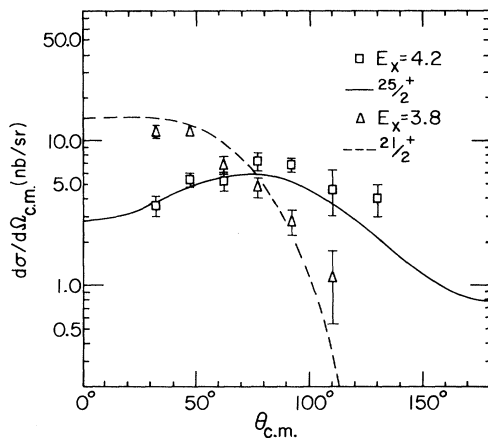


FIG. 2. Comparison of measured (points) and predicted (curves) cross-section angular distributions for the two dominant transitions in  $^{88}\text{Sr}(p, \pi^-)$  at  $T_p = 175$  MeV. The overall normalization of the calculated absolute cross sections has been adjusted to agree with the measurements while holding the ratio of the two distributions fixed.

150–200 keV, dominated by the energy spread in the incident beam. A proton bombarding energy  $T_p = 175$  MeV was chosen in order to match the outgoing pion energies for this reaction with those of earlier measurements<sup>4</sup> on  $^{48}\text{Ca}$ .

Shown in Fig. 1 are two representative  $^{88}\text{Sr}(p, \pi^-)$  spectra observed at laboratory angles of  $45^\circ$  and  $90^\circ$ . The inset in each case displays the model predictions for the low-lying states in  $^{89}\text{Zr}$  appropriate for that angle. The two strongest peaks in the calculated spectra correspond to an  $L = 12$  transition to the stretched  $25/2^+ (\pi g_{9/2})^2 (\nu g_{9/2})^{-1}$  state at  $E_x = 4.10$  MeV, and an  $L = 10$  transition to a  $21/2^+$  state at  $E_x = 3.71$  MeV.<sup>9</sup> The latter dominates at forward angles, while the former is most prominent at backward angles. These two states in  $^{89}\text{Zr}$  have not been previously identified [although a  $23/2^+$  state of similar configuration—a victim of  $J = L - \frac{1}{2}$  suppression in the  $(p, \pi^-)$  calculations—has been identified at  $E_x = 3.58$  MeV in  $(\alpha, xn\gamma)$  studies<sup>10</sup>]. The observed spectra in Fig. 1 do indeed exhibit two prominent peaks with the expected angle-dependent relative strength. Their energy centroids, averaged over all angles measured, are 4.18 and 3.81 ( $\pm 0.08$ ) MeV. Within the 70–80-keV uncertainties in both the experiment and the model calculations,<sup>7,9</sup> the measured excitation energies agree well with the predictions for the  $21/2^+$  and  $25/2^+$  states.

Measurements and predictions for the differential cross sections are presented in Fig. 2 for the two strongest  $(p, \pi^-)$  transitions. The peak areas for

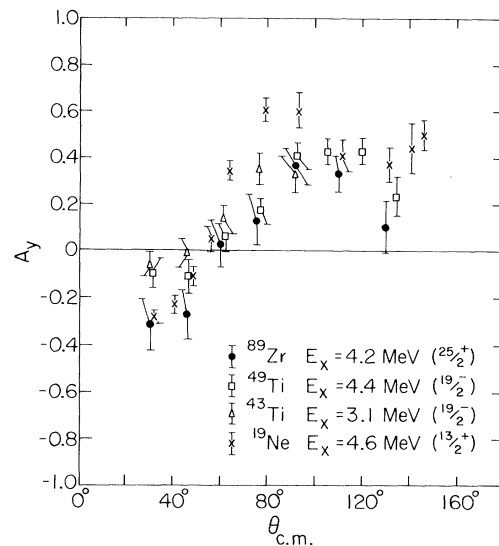


FIG. 3. Analyzing-power distributions measured for two-particle, one hole stretched-state transitions in  $(p_{\text{pol}}, \pi^-)$  reactions on  $^{18}\text{O}$  (Ref. 11),  $^{42,48}\text{Ca}$  (Ref. 4), and  $^{88}\text{Sr}$ , showing an apparent mass-independent signature.

the experimental points were determined by fitting Gaussian shapes superimposed on a linear background to the observed excitation spectra. The cross-section error bars reflect both statistical and estimated fitting errors. There is in addition an estimated normalization error in the cross sections of  $\pm 12\%$ , dominated by uncertainties in solid angle and target thickness. The absolute magnitude of the predicted cross sections is arbitrary, but the *relative* values for the two transitions are plotted as given by the calculations for  $R_0 = 4.1$  fm. The general agreement between the measured and predicted angular distributions in Fig. 2 is remarkably—perhaps fortuitously—good. When combined with the successful application of the same model in the calcium region<sup>3</sup> and the general systematic observation of high-spin two-particle, one-hole state selectivity for  $(p, \pi^-)$  on lighter nuclei,<sup>1,2</sup> the agreement in Figs. 1 and 2 is compelling evidence for identifying the states at  $E_x = 4.18$  and 3.81 MeV as  $25/2^+$  and  $21/2^+$   $(g_{9/2})^3$  states in  $^{89}\text{Zr}$ , respectively.

Additional empirical support for this identification is the marked similarity of the analyzing power ( $A_y$ ) distribution (see Fig. 3) measured for the 4.18-MeV state to those measured previously<sup>4,11</sup> for transitions to known stretched states in lighter nuclei. These distributions differ markedly in each case from  $A_y$  measurements for transitions to states of lower spin in the same residual nucleus.<sup>2,4,11</sup> The

model calculations discussed here would have to include distorted waves and/or more detailed reaction dynamics in order to compute analyzing powers. Simple qualitative arguments used previously<sup>12</sup> to explain a  $j$ -dependent sign difference in  $(p_{\text{pol}}, \pi^-)$  analyzing powers for ground-state transitions relied on symmetry-principle constraints which do not apply here, since the final-state protons are not coupled to  $J=0$ . Thus, the mass-independent  $A_y$  signature suggested in Fig. 3 for stretched two-particle, one-hole states produced in  $(p_{\text{pol}}, \pi^-)$  reactions is an empirical observation yet to be explained.

In summary, we have found that the model of Ref. 3, despite its manifest simplicity, provides a good basis for exploiting the natural selectivity of  $(p, \pi^-)$  reactions to identify high-spin two-particle, one-hole states in nuclei. One goal of more sophisticated pion-production theories currently under development should be to explain why one is able to reproduce so many salient features of the data with such crude approximations.

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<sup>9</sup>Independent shell-model calculations for <sup>89</sup>Zr by R. Gross and A. Frenkel, Nucl. Phys. **A267**, 85 (1967), predict excitation energies for the  $(g_{9/2})^3$  states consistent with the predictions of Ref. 7 to within  $\sim 70$  keV.

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<sup>11</sup>J. J. Kehayias *et al.*, Bull. Am. Phys. Soc. **28**, 705 (1983); J. J. Kehayias, Ph. D. thesis, Indiana University, 1983 (unpublished).

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