

threshold region may have important implications for the further understanding of the pion production mechanism as well as future connections to studies in the field of pionic atoms. In the latter regard, from a purely experimental point of view, an understanding of the systematics of  $(p, \pi^-)$  cross sections at (or near) threshold is important for the design of possible future IUCF Cooler Ring experiments, wherein pionic atoms could be created and studied "from the inside out".<sup>3,14</sup>

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#### WHERE IS THE HIGH-SPIN STRENGTH IN HEAVY TARGET $(p, \pi^-)$ REACTIONS?

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An unexpected, selective concentration of discrete high spin reaction strength ( $E_x = 3-6$  MeV) has been shown<sup>1</sup> to be a systematic feature of  $(p, \pi^-)$  spectra obtained from many target nuclei ranging from the 1p shell up to the region  $A \approx 90$ . The strongly excited states were interpreted<sup>1,2</sup> to have a 2 particle (protons) -1 hole (neutron) configuration with respect to the target nucleus ground state, coupled to maximal (stretched), or near maximal spin, in order to

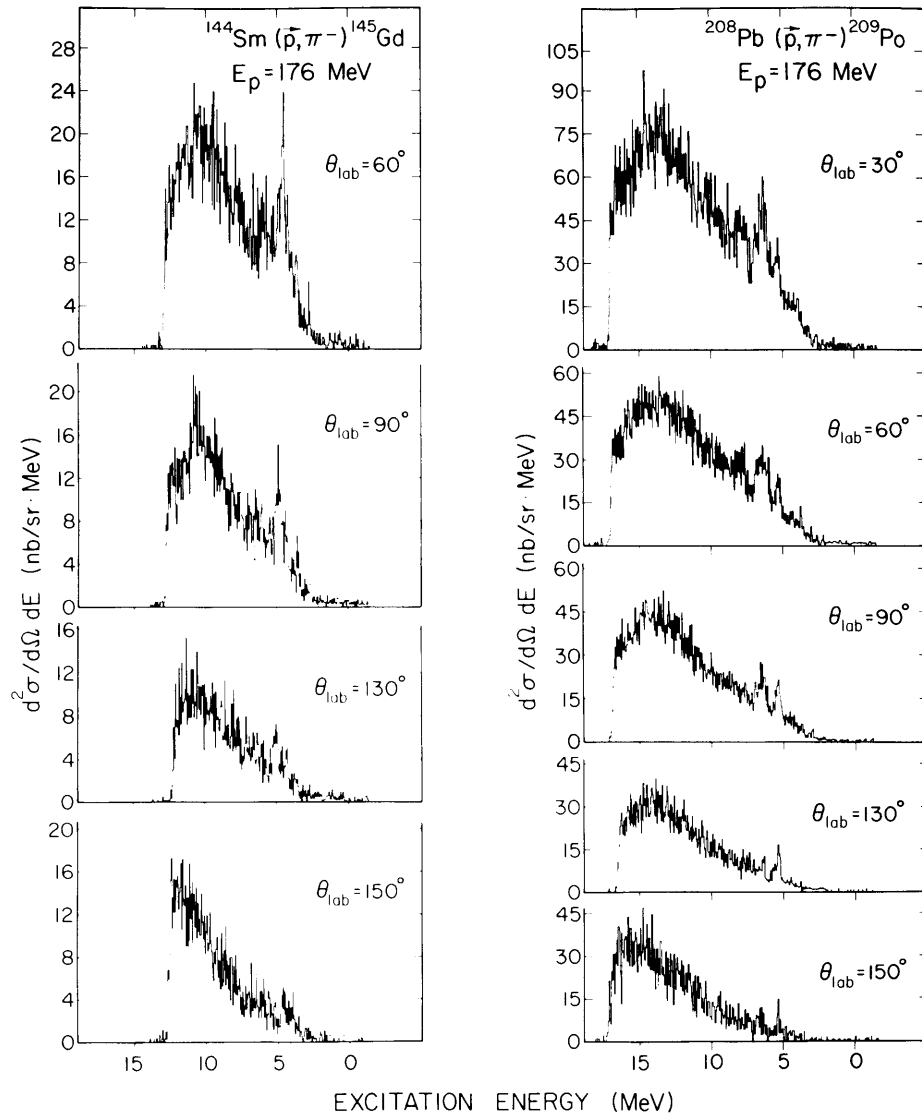
accommodate the large linear and angular momentum mismatch inherent to the  $(p, \pi)$  reaction. The selective population of these states is favored by the assumed dominance<sup>3</sup> in the reaction mechanism of the fundamental and unique two-nucleon process  $p + n \rightarrow p + p + \pi^-$ , where the incident proton interacts with a target neutron from a specific shell model orbital. The resulting spectrum of discrete 2p-1h configuration states is largely determined by the number of available

high-spin "target" neutrons, and corresponding high-spin orbitals in which to place the protons. An effective "Δ-window" is imposed on the lower side by the large momentum mismatch and on the upper side by the maximum spin transfer available from the three interacting "particles" in a given high-spin subshell. These general features have been well described for the systematic data obtained in the calcium region using a crude plane wave model with a localized peripheral interaction and reliable shell model wave functions.<sup>4</sup>

More detailed experimental studies of this phenomenon have since been carried out with sufficiently good resolution to delineate the fine structure in the oxygen,<sup>5</sup> calcium,<sup>6</sup> and most recently the zirconium<sup>7</sup> regions, corresponding to 2p-1h configurations (1d<sub>5/2</sub>)<sup>3</sup>, (1f<sub>7/2</sub>)<sup>3</sup>, and (1g<sub>9/2</sub>)<sup>3</sup>, respectively. For <sup>88</sup>Sr(p,π<sup>-</sup>)<sup>89</sup>Zr, where two distinct discrete peaks were observed<sup>7</sup> (separated by ~ 370 keV) at the beginning of a nearly linearly rising continuum, the pronounced selectivity of near threshold (p,π<sup>-</sup>) was exploited to identify previously unknown high-spin (g<sub>9/2</sub>)<sup>3</sup> states in <sup>89</sup>Zr. The higher lying state at E<sub>x</sub> = 4.18 MeV (identified as the stretched 25/2<sup>+</sup> state predicted by Brown<sup>7</sup> at 4.1 MeV) dominates the spectrum at the more backward angles. It has a relatively flat angular distribution as expected in a plane wave model for the transition with the largest total L transfer (L = 12). The state at lower excitation is identified as the 21/2<sup>+</sup> state (L = 10) and has a cross section angular distribution which is forward peaked, falling off sharply at the large angles. Note: the 23/2<sup>+</sup> state is assumed to have a (model-dependent) suppression arising from angular momentum coupling coefficients,<sup>4</sup> as is in fact observed experimentally for the analogous 17/2<sup>-</sup> state of the (1f<sub>7/2</sub>)<sup>3</sup> configuration in <sup>48</sup>Ca(p,π<sup>-</sup>)<sup>49</sup>Ti.<sup>6</sup>

Momentum matching considerations suggest that population of analogous transitions for (p,π<sup>-</sup>) on heavier mass targets should also be possible. Earlier surveys<sup>1</sup> suggesting that this configuration strength was missing, in fact led to some degree of speculation for its disappearance from the spectrum. The most likely places to look seriously in the heavy mass region are in the samarium and lead regions where the next high-spin neutron orbitals, 1h<sub>11/2</sub> and 1i<sub>13/2</sub>, are filled, leading to the possibility that (1h<sub>11/2</sub>)<sup>3</sup> and (1i<sub>13/2</sub>)<sup>3</sup> configuration 2p-1h states, respectively, would be sampled.

Recently obtained angular distribution data are displayed in the form of double differential cross section spectra for the <sup>144</sup>Sm(p,π<sup>-</sup>)<sup>145</sup>Gd and <sup>208</sup>Pb(p,π<sup>-</sup>)<sup>209</sup>Po reactions in Fig. 1, left and right panels, respectively. The data were taken during two separate running periods with the resulting spectra summed at the largest angle for Pb in order to increase the statistics. Here we see for the first time heavy target spectra which are qualitatively similar to the (p,π<sup>-</sup>) spectra obtained during earlier survey studies of the oxygen-calcium-zirconium regions. In both Sm and Pb cases, there is evidence for a strongly excited group of unresolved residual discrete states at relatively low excitation energy (no evidence for a ground-state transition) and a strongly rising "continuum" cross section. The forward angle discrete cross section strength summed over a region on the order of 1 MeV amounts to 15 and 25 nb/sr for <sup>145</sup>Gd and <sup>209</sup>Po, respectively. This is comparable to the strength observed for lighter mass targets having filled high-spin neutron orbitals.<sup>1</sup> It is clear, however, from the rapidly changing shape with angle of the concentrated strength excitation that for these heavy target cases many levels are contributing to the



**Figure 1.** Double differential cross section spectra for the  $^{144}\text{Sm}(p, \pi^-)^{145}\text{Gd}$  and the  $^{208}\text{Pb}(p, \pi^-)^{209}\text{Po}$  reactions taken at several lab angles for 176 MeV proton bombarding energy.

cross section in this energy region. Some few of the discrete transitions involved still show some strength (although only of order a few nb/sr) at the largest measured laboratory angles. The problem of observing these transitions previously appears to be associated with the general difficulty of measuring relatively small cross sections for such heavy targets, exacerbated by the fact that the continuous part of the cross section extends well below the excitation energy region of the discrete states, providing a strong "background" for the measurement.

How can one attempt to distinguish the stretched state configurations among the several discrete transitions unresolved experimentally at the forward angles? It is already clear that this is somewhat more difficult than was the case for the lighter mass regions. Were the Brown, Toki, Scholten plane wave model<sup>4</sup> to apply for the heavy targets, then at least qualitatively, angular distributions for transitions to these stretched states would be governed by the behavior of the relevant spherical Bessel functions (here of order 15 and 18, for the Sm and Pb, respectively) in the region of the nuclear surface. These states should be favored since they are the ones which are well matched at the nuclear surface. In general they should also show a much greater strength at the larger angles, relative to transitions of lower total L, owing to a cross section distribution which is relatively flat with angle.

From a different tack, the analyzing power distributions for the stretched configurations reached by the  $(p, \pi^-)$  reaction in the oxygen, calcium, and zirconium regions, exhibit an experimentally determined universal behavior<sup>7,8</sup> corresponding to a stretched state "signature"; namely small or negative  $A_y$  at

forward angles, rising to a substantial positive  $A_y$  (.2-.4) beyond roughly 60-70 degrees.

Hence conditions expected to emphasize the stretched configurations are reflected in spectra obtained at a fairly backward (beam left) angle with spin up incident protons and shown in greater detail in Fig. 2 for the two targets. Predictions for the stretched state positions are indicated by the arrows. In the case of Pb, we indeed see a weak peak ( $E_x = 6.4$  MeV) near the predicted<sup>9</sup> stretched state excitation

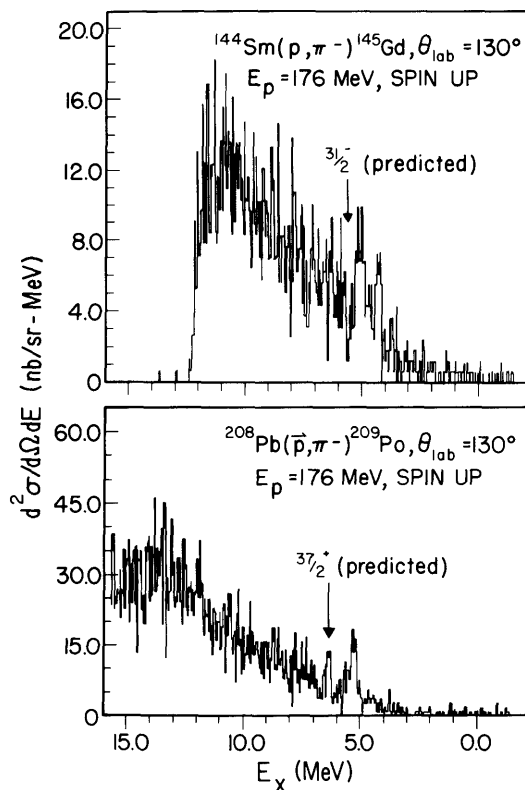


Figure 2. Spin up double differential cross section spectra for the  $^{144}\text{Sm}(p, \pi^-)^{145}\text{Gd}$  and  $^{208}\text{Pb}(p, \pi^-)^{209}\text{Po}$  reactions at  $\theta_{\text{lab}} = 130^\circ$ . Previous shell model predictions<sup>9,10</sup> for the location of the  $31/2^-$  and  $37/2^+$  stretched states with configurations  $(1h_{11/2})^3$  and  $(1i_{13/2})^3$ , respectively, are indicated by the arrows.

energy (the latter based on simple considerations of the relevant single hole and two particle excitations in neighboring nuclei). It has an analyzing power that is substantially positive at  $130^\circ$  and a cross section distribution which is consistent with its being fairly flat in the angular range  $130^\circ - 150^\circ$ . Thus, the 6.4-MeV peak may indeed be a  $37/2^+$  candidate state exhibiting strength of the  $(1i_{13/2})^3$  configuration. At somewhat lower excitation energy we observe the persistence of an additional peak,  $E_x = 5.3$  MeV, in the low statistics spectrum obtained at the largest angle (see Fig. 3). This level appears to be the most significant component of a group of states observed near this excitation in the  $130^\circ$  spectrum. This  $E_x = 5.3$ -MeV peak has a slightly positive  $A_y$  at  $130^\circ$ , but falls off in cross section strength by about 30% in

going from  $130^\circ$  to  $150^\circ$ . Because of the spectral uncertainties, it is unclear whether this level might be considered a fragment of the stretched configuration or a state of lower total spin. The rapid increase in the number of discrete states apparently populated in this excitation region as one goes to more forward angles (see Fig. 1) precludes establishing more globally the behavior of the angular distributions (for either of these states). Hence, identification based on the simple arguments outlined above are much less persuasive than was the case in studies of lighter targets. For Pb, the situation may be additionally complicated by the presence of quite a few relatively high-spin filled neutron and empty proton orbitals, (e.g.,  $1h_{9/2}$ ,  $2f_{7/2}$ , etc.). These orbitals can

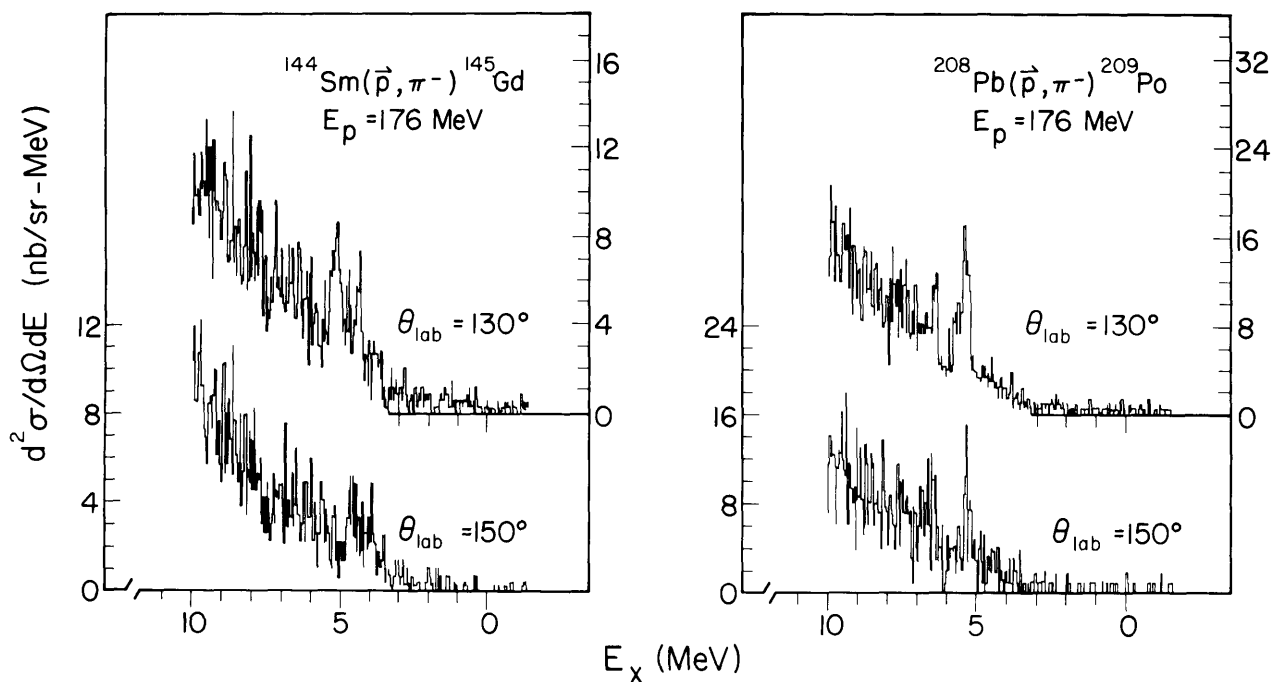


Figure 3. Double differential cross section spectra for the  $^{144}\text{Sm}(p, \pi^-)^{145}\text{Gd}$  and the  $^{208}\text{Pb}(p, \pi^-)^{209}\text{Po}$  reactions obtained at the most backward angles.

contribute cross-shell configuration states of moderately high spin adding to the the spectral complexity at the larger angles. Such cross-shell transitions, however, were not observed in the  $(p, \pi^-)$  studies of the calcium region, where the lowest-lying available proton orbital is that corresponding to the filled high-spin neutron shell.

Similar arguments apply generally to the Sm case, although here there are no competing empty proton high-spin sub-shells other than the  $1h_{11/2}$  orbital of interest. The prediction<sup>10</sup> for the stretched  $31/2^-$  state at  $E_x = 5.79$  MeV [configuration  $(1h_{11/2})^3$ ] is a result of a realistic shell model calculation, yet is some .5 MeV away from the highest-lying, strongly excited discrete states in the  $130^\circ$  spectrum (see Fig. 2). The nucleus  $^{145}\text{Gd}$  is of particular interest since it is one neutron away from  $^{146}\text{Gd}$  which exhibits some properties of double shell closure. Because of experimental difficulties in this mass region, little is known about the stretched and nearly stretched  $2p-1h$  configurations from more conventional  $(\text{HI}, x\text{n}\gamma)$  measurements.

A comparison of spin up and spin down spectra at  $\Theta_{\text{lab}} = 130^\circ$ , as well as a comparison to peak width systematics, indicate that the higher lying structure in the  $130^\circ$   $^{145}\text{Gd}$  spectrum is a doublet. The higher lying member of the doublet (estimated to be at approximately  $E_x = 5.24$  MeV) appears to have a strongly positive analyzing power at  $130^\circ$ , whereas the lower lying member (estimated to be at 5.08 MeV) has an analyzing power near zero at this angle. Although the higher lying member of the doublet is about .5 MeV lower in excitation than the predicted  $31/2^-$ , its separation from the lower member agrees well with the predicted separation<sup>10</sup> ( $\approx 0.28$  MeV) of the  $31/2^-$  from the second  $27/2^-$  state in  $^{145}\text{Gd}$ . In analogy to lighter

target cases, these two states should be the two largest peaks in the spectrum (the  $29/2^-$  is suppressed by coupling coefficients<sup>4</sup>) at these large angles.

However, a look at the  $150^\circ$  spectrum (Fig. 3) shows that neither member of this doublet is strongly excited at the largest angle. In fact the only state surviving with about the same strength as in the  $130^\circ$  spectrum is the relatively weak state at  $E_x = 4.7$  MeV (and to a much lesser extent the state at 4.3 MeV). However, it appears that  $A_y$  is nearly zero for the 4.7-MeV state and slightly positive for the 4.3-MeV state. As was the case for the Pb spectra, the statistics for the relevant states at the largest angles are really quite poor (cross sections here are the order of 1 nb/sr!). If these lower-lying states that persist in the largest angle  $^{145}\text{Gd}$  spectrum (the 4.7 MeV state in particular) were indeed the highest spin states of the  $(1h_{11/2})^3$  configuration, they would be significantly far away in energy from their shell model calculated positions.

In summary, these data suggest the observation of high-spin states with  $2p-1h$  configurations  $(1h_{11/2})^3$  and  $(1i_{13/2})^3$  in Gd and Po, respectively. Systematics of stretched configurations observed in  $(p, \pi^-)$  studies on lighter mass targets were used in an attempt to identify stretched state candidates in  $^{145}\text{Gd}$  and  $^{209}\text{Po}$ . States at 6.4 (and possibly 5.3 MeV) in  $^{209}\text{Po}$  and 4.7 (and possibly 4.3 MeV) in  $^{145}\text{Gd}$  are such candidates. At present, however, neither the resolution nor large angle statistics obtained are sufficient to enable one to produce a significant portion of the angular distribution in order to attach much certainty to our speculations. (It should be noted that the IUCF Cooler ring may, in principle at least, be able to help with the resolution problem.) Since this choice of targets was in some sense optimal, in terms of having a filled

high-spin neutron orbital, with the corresponding proton orbital empty, it seems that it will be difficult to use  $(p, \pi^-)$  as a spectroscopic tool in these higher mass regions.

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