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EXCITATION OF STRETCHED AND NEARLY STRETCHED PARTICLE-HOLE STATES

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Abstract - A detailed comparison of the \((p,p')\) excitation of high-spin states in \(^{28}\text{Si}\), for \(E_p = 80\) to \(180\) MeV, with DWIA calculations is summarized, from the point of view of extracting the spectroscopic strengths of the transitions. Some recent nuclear structure calculations relating to these strengths are discussed.

First I want to review with you the question of how well current DWIA calculations fit the experimental data for inelastic proton scattering in the energy range \(80\) to \(180\) MeV, and the related question of how reliably the transition strengths can be extracted. Then I will discuss whether our current understanding of nuclear structure is adequate for the description of the strengths that seem to be derived from the data.

Three high-spin states in \(^{28}\text{Si}\) will be discussed in detail: the 6\(^{-}\), \(T=1\) state at 14.35 MeV, the 6\(^{-}\), \(T=0\) state at 11.58 MeV, and the 5\(^{-}\), \(T=0\) state at 9.70 MeV. The 6\(^{-}\) states have maximum angular momentum for one-particle-one-hole states at 1 MeV excitation, and are therefore called "stretched"; excitation of these states involves transfer of one unit of intrinsic spin, as well as a maximal flip of orbital angular momentum. The 5\(^{-}\) state is "nearly stretched" and is largely a non-spin-flip transition.

At large momentum transfer these stretched and nearly stretched particle-hole states are among the strongest in the inelastic scattering spectrum. The silicon \((p,p')\) spectrum for a momentum transfer of about 350 MeV/c is shown in Fig. 1. As another example, Fig. 2 shows \(^{208}\text{Pb}(p,p')\) at about 480 MeV/c. The high-spin particle-hole states have cross sections comparable to that for the very collective 3\(^{-}\) state.

Since we shall be discussing the appropriateness of the DWIA and the ingredients that are conventionally used in it, it is only fair to make an experimental caveat. These prominent particle-hole excitations occur at fairly high energy, where the density of states of lower angular...
momentum is large, and there is always a background. Resolution is limited and the background is not flat, leading to some ambiguity in extracting the experimental cross sections for all but the strongest states. Furthermore, the particle-hole peaks are not prominent in all cases, leading to questions of fragmentation of the strength.

Comparison of results from scattering of different projectiles has been very helpful since different probes have different excitation matrix elements, the hadronic probes have different reaction-mechanism uncertainties, and the experimental difficulties are also somewhat different for the different reactions.

A detailed investigation of how well the DWIA does for the description of the excitation of these three high-spin states in $^{28}$Si has been carried out by Prof. Catherine Olmer at Indiana and her collaborators /1/. Cross sections and analyzing powers were measured at 80, 100, 135, and 180 MeV. Elastic scattering measurements were done at the same energies, and phenomenological optical models were constructed. It was found that, with good data covering a wide range of angles (we went out to at least 550 MeV/c), with the constraint of a smooth variation of the parameters with energy, and with the important further constraint that the derived total reaction cross sections varied smoothly with energy and were in approximate agreement with the experimental systematics, that the optical model parameters were then well determined.

For inelastic proton scattering we compare the data to calculations made using the distorted-wave impulse approximation (DWIA) /3,4/, and sometimes to variants and improvements of DWIA. In addition to the distorted waves there are two other crucial inputs to DWIA calculations: the structure of the states, as exemplified by the transition form factors, and the effective interaction. Transition form factors have been determined from $(e,e')$ for the $5^-$, $T=0$ /6/ and $6^-$, $T=1$ /7/ transitions, and are consistent with $L=5$ harmonic oscillator densities, with oscillator parameters of 1.91 and 1.74 fm, respectively. For the $6^-$ states we assume in the calculations that the ground state of $^{28}$Si has a filled $d_5/2$ shell, while for the $5^-$ transition we adopt the open-shell RPA transition density of Yen /8/.

There are now available several choices for the effective interaction $t$-matrix to use in DWIA. These are all derived from nucleon-nucleon scattering data, but with different procedures and different selections and weightings of the free scattering data. Results will be shown which use interactions due to Love and Franey (LF) /9/, a free-space interaction derived by Geramb and collaborators /10/ from the Paris potential /11/, a density-dependent interaction, also from the Paris potential via Hamburg /12/, an energy-independent free interaction due to Picklesimer and Walker /13/, and another density-dependent interaction from Geramb, based on the Hamada-Johnston potential /14/.

There is one correction to DWIA that is rather well established: the effective interaction is in principle density dependent, and the effects of this density dependence for a number of isoscalar low-spin natural-parity transitions have been shown to be important by Kelly and his collaborators /5/. Including the density dependence in a local-density approximation seems to give a definite improvement. With that one caveat, one has had the impression that the DWIA works quite well for medium energy $(p,p')$, even for energies as low as 100 MeV. One would like to know if it is possible to calibrate the DWIA so that it can be used to determine the strengths of the nuclear excitations.
In Fig. 3 (top) we see a comparison with the data of the peak cross section predictions for the $5^-$ transition in $^{28}\text{Si}$, and we see that the way the direct and knock-on exchange amplitudes combine can be very different for the different interactions. For this excitation the predicted total results do not vary very much. For the $6^-$ transitions the variations are somewhat larger: the $6^-, T=1$ transition is shown in the lower part of Fig. 3. Even when the predicted peak cross sections are similar, results for other observables may differ more widely.

The differential cross sections for these high-spin states have a characteristic bell-shaped form quite different from the diffraction-like shapes seen for states of

![Energy dependence of the peak cross sections for (p,p') excitation of the 5^-, T=0 and 6^-, T=1 states in 28Si. The separate contributions of direct and exchange processes are indicated for the DWIA calculations. For the data (extreme right) a smooth curve has been drawn through the experimental points for each transition.](image-url)
lower spin. The data is shown in Figs. 4-6. The middle and bottom parts of these

Fig. 4. Cross sections for \((p,p')\) excitation of the \(5^{-}\), \(T=0\) state of \(^{28}\text{Si}\). The curves are from DWIA calculations using optical potentials appropriate for the various energies. Those for the Love-Franey interaction (top) and the free Paris interaction (middle) have been multiplied by 0.667, while those for the density-dependent Paris interaction (bottom) have been multiplied by 0.625.
Figure 5. Cross sections for \((p,p')\) excitation of the \(6^-, T=0\) state in \(^{28}\text{Si}\). The curves are from DWIA calculations using optical potentials appropriate for the various energies. Those from the Love-Franey interaction (top) have been multiplied by 0.15, those for the free Paris interaction (middle) by 0.10, and those for the density-dependent Paris interaction (bottom) by 0.114.
Fig. 6. Cross sections for (p,p') excitation of the 6-, T=1 state in $^{28}$Si. The curves are from DWIA calculations using optical potentials appropriate for the various energies. Those for the Love-Franey interaction (top) have been multiplied by 0.30, while those for the free Paris (middle) and density-dependent Paris interactions (bottom) have been multiplied by 0.50.
figures compare the data to calculations using the free and density-dependent Geramb-Paris interactions. For all three transitions the differences are small, which is consistent with the transition form factors being peaked in the surface of the nucleus. Density dependence is not an important effect for these cross sections, though, as we shall see later, the analyzing powers are somewhat more sensitive.

The various forms of the effective interaction are not equally successful in fitting the shapes of the cross sections, however. The $5^-$ data is compared with the Love-Franey predictions in the top part of Fig. 4, and it can be seen that the predicted curve is too narrow. The Paris calculations (middle and bottom) fit the width of the distribution better, and the difference comes from a bigger second lobe of the central force. Even though the spin-orbit force gives the biggest contribution to the peak cross section, we can learn something about one of the weaker components.

For the $6^-$, $T=0$ state the oscillator parameter chosen may have been a little too large (since there is no $(e,e')$ transition density available, we chose it the same as for the $T=1$ state). All the predicted distributions may be a little too narrow, but the principle deficiency is that the data show a shift with bombarding energy of the q-value of the peak cross section—it shifts to lower q as the energy gets smaller—that is not given by any of the calculations.

In the case of the $6^-$, $T=1$ transition the q-value of the peak is given reasonably well by all the calculations, but there seem to be extra counts at low q at the two lowest energies. These could be from an unresolved state, but similar behavior was seen in the RCNP data at 65 MeV, even though the resolution was better /15/. The Love-Franey calculations fit rather well at 180 MeV, but the tensor contribution seems to deviate from the data at lower energies. The Paris calculations give too broad a distribution.

Our group has already noted /8/ that for a high-spin isoscalar natural-parity transition, like the $5^-$ state in $^{28}$Si, the analyzing power is already large in the plane-wave limit and crosses through zero where the central force term changes sign. Distortion does not change this characteristic shape. Love and Franey /9/ stressed that this should be a general feature for states of this type. Fig. 7 shows the $5^-$ data together with that for a very prominent peak at 3.5 MeV excitation in the $^{116}$Sn$(p,p')$ spectrum (see van der Werf, et al. /16/). We think the tin peak is mainly due to a $9^-$ state at 3.52 MeV /17/, but there may be contributions from nearby $10^+$ and $8^+$ states.

A comparison of the $5^-$ analyzing power with calculations based on various interactions is shown in Fig. 8. All the interactions reproduce this signature at the higher energies, and all deviate more from the data at the lower energies. There is a definite difference at the lower energies between the free and density-dependent Paris interactions, with the density-dependent fitting the data somewhat better. To isolate density dependence one should compare calculations based on the same family of interactions: for these transitions differences between predictions of forces from different families are often much greater than the effects of density dependence. The analyzing power is more sensitive than the cross section to the effects of density dependence because it requires (in the plane-wave limit) interference between two different force components.

For the $6^-$ transitions the situation is more complicated, since in the plane-wave limit the analyzing power is predicted to be small, and distortion is important. However, one seems to see in the analyzing power data for isovector stretched transitions also a characteristic signature. Fig. 9 shows data for the $6^-$, $T=1$ state in $^{28}$Si together with some data for the excitation of its analog in the $(p,n)$ reaction, from the Kent State group /18/. The characteristic rise near 450 MeV/c is evident in the Love-Franey calculations (Fig. 10), but the calculated values do not rise enough to match the data. Calculations using the other interactions do not do as well, at least at the higher energies.
Now let's return to the question of what are the strengths of these transitions. Before looking at the silicon results in detail I would like to mention results for other high-spin transitions. Stretched transitions in several nuclei have been studied by (p,p') now, and while most have been examined at only one bombarding energy, and compared with calculations using only one effective interaction, the results usually require a normalization factor of between 0.3 and 0.5 (see, e.g., /19/). For example, Comfort et al. /20/ have located two close-lying 8- states in 48Ca and they are reported to sum up to 0.38 of the strength expected from a filled f7/2 neutron shell. Some of the 0 0 stretched states found in (p,n) by Anderson et al. /21/, are shown in Fig. 11. Their calculations require renormalization by factors of $\lesssim 0.5$. The 0 0 stretched states lie lower in the level schemes than 1 hw states and may thus be less fragmented. The 14- state in 208Pb was earlier /2,19/ found to need a normalization factor of about 0.5 at 135 MeV, and recent work from Osaka at 65 MeV finds a similar result by comparison with a G-matrix force /22/. In this last work, by the way, two-step contributions were calculated and found not to be important.

To return to the transitions in silicon, we show in Fig. 12 the normalization factors necessary to adjust the calculated peak cross sections to fit the data. For the 5- transition all the interactions (except perhaps Picklesimer-Walker at 180 MeV) give the same factor, approximately independent of bombarding energy. The value found, between 0.6 and 0.7, is smaller than was found with electron scattering /6/, where it was within 10% of unity, but that's not so very disturbing, since while the (e,e') results determine the longitudinal transition density very well they only place crude bounds on the transverse density, which is relatively more important in (p,p'). It is perhaps somewhat more disturbing that 800-MeV results for this transition /23/ seem to need no renormalization, but at that bombarding energy again the longitudinal density is more emphasized. The largest uncertainty in describing this transition may come from uncertainties in the ground-state properties of 28Si.
Fig. 8. Momentum-transfer dependence of the analyzing powers for \( (p,p') \) excitation of the \( 5^- \), \( T=0 \) state in \( ^{28}\text{Si} \). The curves are from the DWIA calculations discussed in the text.

For the \( 6^- \), \( T=0 \) transition the different interactions predict quite different peak cross sections, leading to quite different normalization factors, though none vary strongly with energy. The values found with the Love-Franey interaction are consistent with results from inelastic pion scattering \(^2\), but the \( (\pi,\pi') \) results have been analyzed with only one particular interaction.

In the bottom of the figure we see the results for the isovector \( 6^- \) state. Again the differences are large, and in some cases the energy dependence is not correctly
Ratios of the normalization factors for the two $6^{-}$ transitions are shown in Fig. 13. The energy dependence is well described by the Love-Franey force, which overpredicts the isoscalar/isovector ratio by a factor of about 2. Both calculations using the Paris interaction overpredict this ratio by a factor of about 5.

We must conclude that the extraction of normalization factors, or spectroscopic strengths, from $(p,p')$ excitation of high-spin states is not yet unambiguous. The differences found here between results obtained from the different interactions are disturbing, and we shall probably have to use all the tools we can find, including the study of states of various types, energy dependence, and the study of more complicated spin observables (which bring in interferences between different interaction components) to find an effective interaction that can be relied on.

In the meantime it may still be worthwhile to review some of the ideas about why these states have the strengths they seem to. The $5^{-}$ strength is rather sensitive to the amount of $d_{3/2}$ in the ground state, since the $d_{3/2}^{-}l_{f_{7/2}}$ configuration is largely spin singlet, while the occupation-favored $d_{5/2}^{-}l_{f_{7/2}}$ configuration has only a modest spin-singlet component. A more precise determination of the transverse form factor in $(e,e')$ would be a great help here.

The $6^{-}$ transitions will have their strength reduced by the lack of full occupancy of the $d_{5/2}$ orbital in the ground state; that alone will reduce the normalization factor to somewhere between about 0.50 and 0.75.

While we cannot be sure exactly what the ratio of normalizations is for the two $6^{-}$ transitions, it is clear that the simplest models give them the same value, while both the $(\pi,\pi')$ results and the Love-Franey analysis of $(p,p')$ give isoscalar strength about one half the isovector (and the Paris force analyses of $(p,p')$ give an even smaller factor, 1/5 or 1/6).

It has been pointed out several times /25-27/ that in stripping experiments, starting from the $^{27}$Al ground state, these two states are populated with approximately equal strength, in agreement with simple expectations. It has sometimes been argued that this necessarily implies approximately equal strength in inelastic scattering /27/. That argument suffers from overly restrictive assumptions. If the wave functions of the states involved (ground states of $^{28}$Si and $^{27}$Al, and the two $6^{-}$ states in silicon) are sums of more than one term, so that there are multiple routes for the transitions, then there is no reason to believe that the spectroscopic strengths for stripping and inelastic scattering should be proportional.
Fig. 10. Analyzing powers for \((p,p')\) excitation of the \(6^{-}, T=1\) state in \(^{28}\text{Si}\). The curves are from the DWIA calculations discussed in the text.

For example, Amusa and Lawson /28/ have done a calculation in which in the ground states particles can be in either \(d_{5/2}\) or \(g_{9/2}\), while for the \(6^{-}\) states one particle is transferred to \(f_{7/2}\). They find a substantial fractionation of the strength for both channels. The stripping strength is not proportional to the inelastic scattering strength. They get a somewhat greater quenching for the inelastic strength to the strongest isoscalar state than for the isovector. The set of basis...

Fig. 11. Excitation of the 0\(K_{0}\) stretched states in the \((p,n)\) reaction, from /21/. Spin-parity values are \(7^{+}, 7^{+}, 9^{+}\), and \(13^{+}\), respectively.
states in their calculation is still not large enough that one would feel comfortable in making direct comparisons with the data, but the results are certainly encouraging. As an example of the multiple routes possible for the transitions, Fig. 14 shows a truncated set of the wave function components involved.

Another approach, also restricted to valence-shell effects, is suggested by all the evidence that $^{28}$Si is a deformed nucleus. Zamick /29/ has noted that a $J=6$ configuration in a deformed nucleus is split into 7 components, with K values running from 0 to 6, and that the inelastic scattering strength is distributed, with 2/13 of the total going to each K component between 1 and 6, and 1/13 to the K=0 level. The stripping is more complicated, since it starts from $^{27}$Al, which has some definite K value or mixture of K values. Transfer of an f$_{7/2}$ proton cannot connect an initial K of 1/2 or 3/2 to K=6, for example, and in general the population of the
The calculation I have done has a limited basis, with the hole restricted to the \(d_{5/2}\) shell and the particle to \(f_{7/2}\). The effects of deformation and of the Coriolis force have been included. The only distinction between \(T=0\) and \(T=1\) is that a residual particle-hole interaction was added in the form of the modified surface delta interaction, which gives approximately the splitting between \(K=0\) and \(K=6\) is only about 2–3 MeV. On the other hand, the off-diagonal Coriolis matrix elements that admix adjacent \(K\)-values are all larger than about 3.5 MeV.

The results for inelastic scattering strength are shown in Fig. 15, and show that typically something like 1/2 of the total strength is collected into one state. In this simplified calculation the difference between isoscalar and isovector is not very large. The results for stripping strength are shown in Fig. 16. The description of \(^{27}\text{Al}\) is done in the same simplified way, but the results are in reasonable agreement with this of Dehnhard /31/. Again the \(T=0\) results do not differ very much from those for \(T=1\) for the strength of the principal transition. One can see that there are differences in detail between the inelastic scattering and stripping strengths from Fig. 17.

This model is, of course, too simplified to be directly compared to the data in any realistic sense. There are the problems of what the deformations are, and how one handles the differences in deformation between the different states. The basis should be enlarged, bringing in real Nilsson states mixed in \(\lambda\) and \(j\). And a more
realistic residual interaction should be used, with off-diagonal matrix elements. But I think the model has a certain amount of interest in its exploration of the effects of deformation; deformation is likely to play a role for those transitions, even if it may be better in the end to treat it via indirect (shell-model) means.

The effects discussed so far have all involved the valence shell. There may also be effects associated with $6^-$ strength at $3\Delta$ and $5\Delta$, and possibly in the delta region. A recent calculation of Blunden, Castel, and Toki /32/ considers such effects. They find, as was already indicated by the Julich group /33/, that delta-hole admixtures have a much smaller effect for these high-spin states than they do for Gamow-Teller and M1 strength. On the other hand, they report that $3\Delta$ mixing produced by a Landau-Migdal force reduces the isoscalar $6^-$ strength by about 25%, while it has a much smaller effect on the isovector strength. It is perhaps puzzling that the effect is attributed to a stronger repulsive force in the isoscalar channel, but in fact the strong isoscalar state lies 2.8 MeV below the strong isovector strength.

To summarize, there are perhaps more difficulties than had earlier been thought in extracting believable spectroscopic factors from medium-energy proton inelastic scattering, but there is considerable evidence that the strength of the $1\Delta$ excitations in $^{28}$Si is quenched, and that the isoscalar $6^-$ state is quenched more than the isovector. Part of the overall $6^-$ quenching comes from the obvious fact that the $d_{5/2}$ orbital is not fully occupied in the ground state. Differences in quenching between the isoscalar and isovector states can reasonably be expected to come from valence-shell fragmentation, and perhaps from $3\Delta$ mixing, and these mechanisms need not affect the stripping spectroscopic factors in the same way. We are now beginning to have a much more comprehensive understanding of the reaction mechanism for $(p,p')$ and will, I am confident, be able to find an appropriate effective interaction for the DWIA. If we do not yet know how to fix the strengths of these elementary nuclear excitations precisely from nucleon inelastic scattering, and how to understand them, we have made considerable progress toward that goal.

Fig. 15. Distribution of inelastic strength from the simplified deformed model described in the text, for various deformations.
Fig. 16. Distribution of stripping strength from the simplified deformed model described in the text, for various deformations.

Fig. 17. Comparison of inelastic and stripping strength in the simplified deformed model, for a deformation of $-0.4$.

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