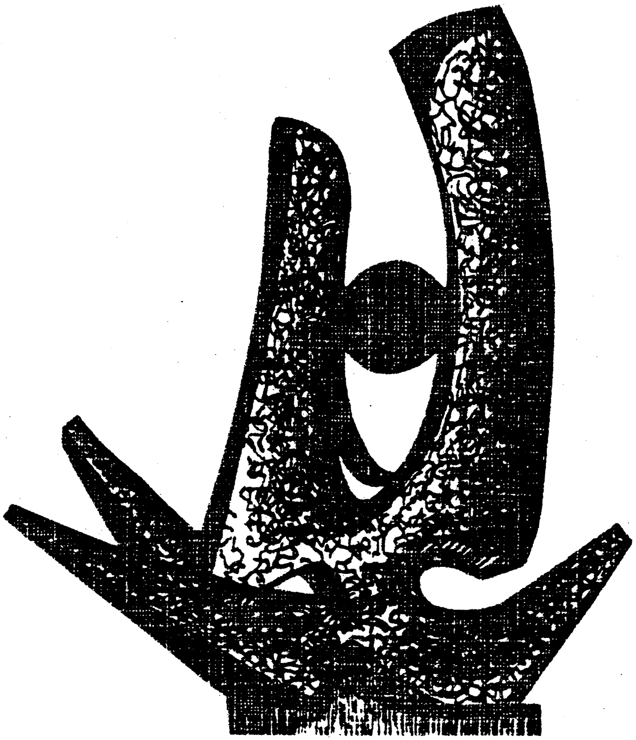
MICHIGAN STATE UNIVERSITY

CYCLOTRON LABORATORY

INELASTIC PROTON SCATTERING AND THE QUENCHING OF $\Delta L=0$ SPIN-FLIP EXCITATIONS IN NUCLEI

N. ANANTARAMAN

Invited talk presented at the International Conference on Nuclear Physics, Bhabha Atomic Research Centre, Bombay, India, December 27-31, 1984.



FEBRUARY 1985

MSUCL-509

INELASTIC PROTON SCATTERING AND THE QUENCHING OF $\Delta L=0$ SPIN-FLIP EXCITATIONS IN NUCLEI

N. Anantaraman

National Superconducting Cyclotron Laboratory
Michigan State University
East Lansing, Michigan 48824-1321

Abstract

The results of 201-MeV (p,p') studies of $\Delta L=0$, $\Delta S=1$ transitions at very forward angles are discussed. Typically, the observed strength is 25% to 30% of that predicted. This is illustrated by data for the Ca isotopes; comparisons with (p,n) and (e,e') measurements are made. The observation, in ^{28}Si, of comparable reduction factors for isoscalar transitions, where Δ-isobar effects must be insignificant, indicates the importance of configuration mixing as a quenching mechanism. This conclusion is consistent with the results of spin-flip cross section measurements using $(\vec{p},\vec{p}')$.

1. INTRODUCTION

During the 1970's, new types of giant electric resonances were discovered and studied$^{1)}$, in addition to the giant dipole which had been known for a long time. These resonances added to our knowledge of nuclear collective motion in which only the spatial degrees of freedom of the nucleons are involved. In the 1980's, the emphasis has shifted to the study of magnetic resonances, viz. those that involve the spin degrees of freedom of the nucleons. They have been excited by a variety of probes, including (e,e'), (γ,γ'), (p,p') and (p,n), every one of which has added to our knowledge of spin

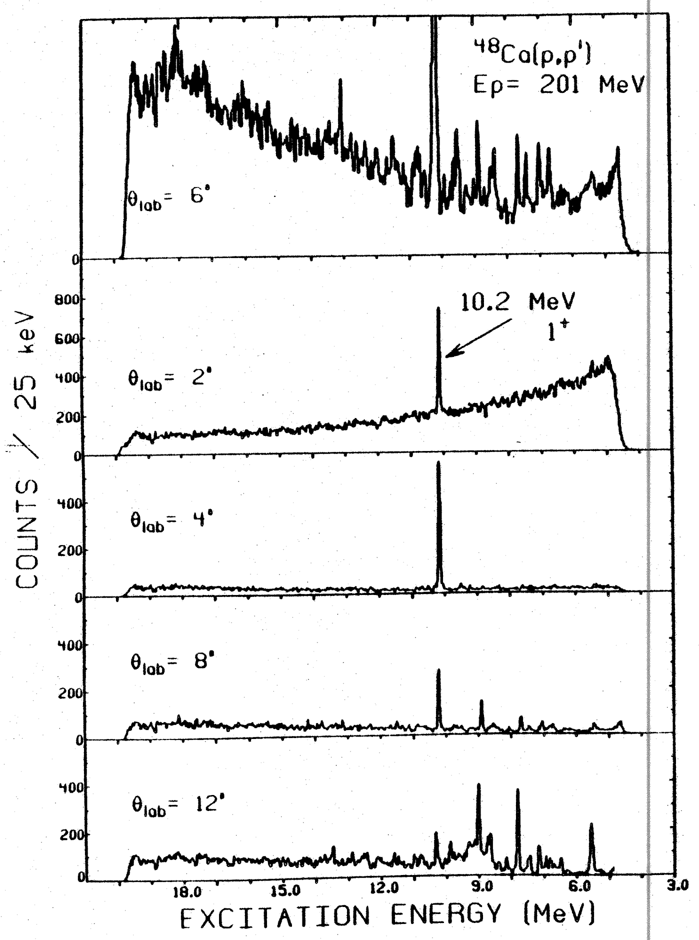


Fig. 1 - Spectra of protons inelastically scattered from ^{48}Ca. The uppermost spectrum has been scaled to show the weakly excited states.

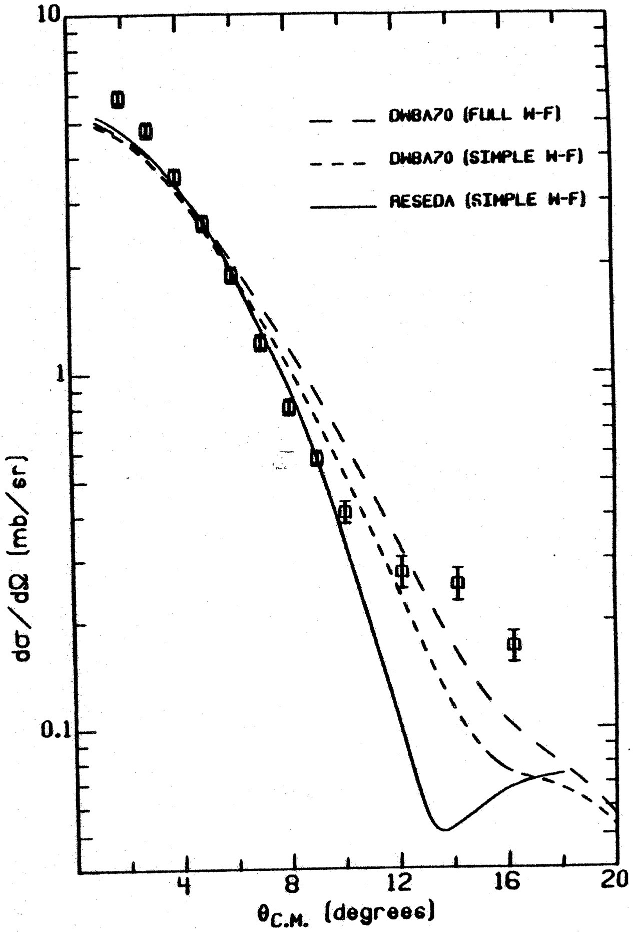


Fig. 2 - Angular distribution for ^{48}Ca (p,p') to the 10.2 MeV state. The points are the measured values and the curves are from calculations described in the text.

excitations $^{2,3)}$. This paper will focus on the results obtained with inelastic proton scattering at 201 and 319 MeV. The transitions of interest (for an even-even target) are of the type $0^+ \to 1^+$, which involves the transfer to the nucleus of one unit of spin angular momentum but of no orbital angular momentum$^{4)}$.

Some of the reasons for the interest in studying 1^+ states may be understood by considering a spin-unsaturated nucleus (one with an occupied $j_> = \ell + 1/2$ orbit and an empty $j_< = \ell - 1/2$ orbit). In such a nucleus, the 1^+ state is a simple mode of excitation in which a nucleon from the $j_>$ orbit is excited to the $j_<$ orbit, the particle and hole then coupling to 1^+. An example is ^{48}Ca, the ground state of which consists to a good approximation of 8 neutrons in the $1f_{7/2}$ orbit. The 1^+ state is formed by exciting one of the neutrons to the spin-orbit partner level $1f_{5/2}$. Spin pairings (ground-state correlations) in ^{48}Ca leads to partial occupancy of the $f_{5/2}$ level in the ground state, which turns out to have the effect of reducing the $0^+ \to 1^+$ strength. The energy of the 1^+ state depends on the spin-orbit splitting of the $f_{7/2}$ and $f_{5/2}$ orbits plus some residual interaction. Thus the <u>location</u> of the state measures the effective spin-spin interaction$^{5)}$, while the <u>strength</u> with which the state is excited measures the degree of ground-state correlations$^{6)}$. It has also been proposed$^{7)}$ that the strength reflects the admixture of Δ-isobar components in the low-lying 1^+ wave function; this will be discussed in Sec. 3. It is this possibility, involving the coupling of nucleonic with non-nucleonic degrees of freedom in the nucleus, which accounts for a large part of the interest in spin excitations.

When we began the (p,p') work in 1981 at Orsay$^{8)}$, the initial motivation was to find the kinematic conditions under which $0^+ \to 1^+$ transitions are strongly excited. These conditions were found to be a high bombarding energy (E_p = 200 MeV) and very forward angles (θ_{lab} = 2°-5°). Fig. 1, which shows ^{48}Ca (p,p') spectra$^{9)}$ at a number of angles, is a beautiful illustration of how the (p,p') reaction at small angles selectively excites 1^+ states. Fig. 2 shows the angular distribution of the 1^+ state at 10.2 MeV. The way in which such (p,p') data are analyzed and the strengths of the $0^+ \to 1^+$ transitions obtained is presented in Sec. 2 by reference to our data on the Ca isotopes. Typically, only about one-third to one-fourth of the predicted strength is found, not only for the Ca isotopes but for several other nuclei in the mass range $40 \leq A \leq 140$ for which we could reasonably analyze the data using simple wave functions^{10}). For the closely related Gamow-Teller transitions excited by the (p,n) reaction in a wide variety of nuclei spread over the periodic table, only about 60% of the expected strength is observed^{2,3}).

Thus the quenching of the spin transfer strength to 1^+ states appears to be a general feature in nuclei. The elucidation of the mechanism(s) responsible for the quenching is perhaps the most important open problem in the field of spin excitations. The mechanisms proposed so far will be surveyed in Sec. 3. In Sec. 4, we shall see how a comparison of quenching in isoscalar and isovector channels in (p,p') throws some light on the problem. Additional light is shed by measurements of spin-flip probability as a function of excitation energy; such data ^{12}) have been obtained using the polarized proton beam at LAMPF and are discussed in Sec. 5.

2. THE Ca ISOTOPES

The isotopes of Ca are expected to show a wide range of behavior. In ^{48}Ca, the 1^+ state is predominantly a one-particle--one-hole (1p-1h) excitation between spin-orbit partner levels. Moreover, it is almost entirely a neutron excitation, so that good correspondence between (p,p') and (e,e') strengths should be expected. [In general, when both proton and neutron excitations contribute, there will not be such a correspondence, because only the spin term contributes to (p,p') at small momentum transfer, while both orbital and spin terms contribute to (e,e'). But in cases where only neutron excitations are involved, there is no orbital part to (e,e').]

In ^{40}Ca, on the other hand, there would be no 1^+ strength in the simplest model of a closed core; and any observed strength must be due to a correlated many-particle--many-hole ground state. Both neutrons and protons would contribute to such a correlated ground state. Thus no correspondence between (p,p') and (e,e') strengths should be expected.

For the Ca isotopes with masses between 40 and 48, we expect[13]) a combination of the above two types of excitation: core excitation as in the case of ^{40}Ca and valence neutron excitation as in the case of ^{48}Ca. Again, no strict correspondence between (p,p') and (e,e') strengths is to be expected.

With these considerations in mind, we have made a comparison study of ^{40}Ca, ^{42}Ca, ^{44}Ca and ^{48}Ca with the (p,p') probe at $E_p = 201$ MeV. The data were obtained with the highly developed detection system of the Orsay spectrometer magnet, which allowed us to take

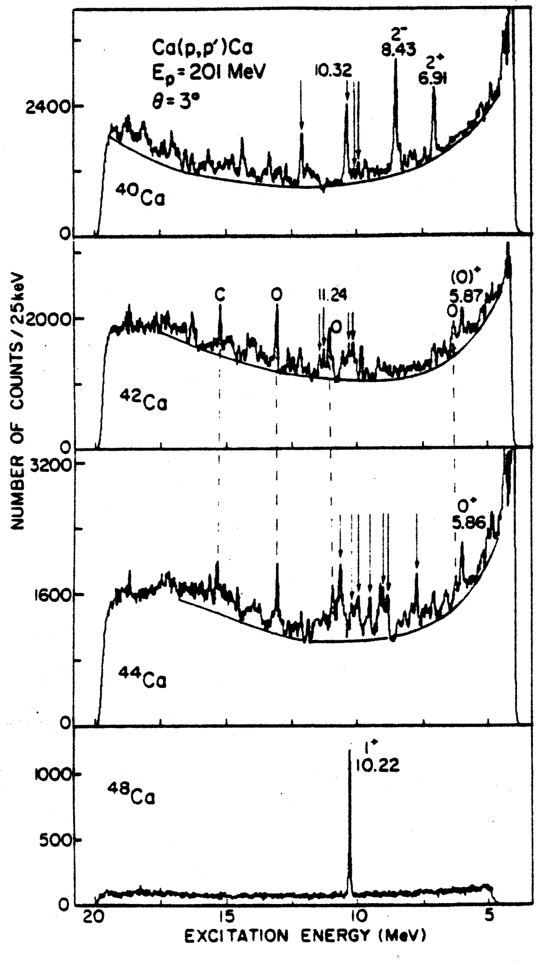


Fig. 3 - Spectra of protons inelastically scattered from ^{40}*Ca,* ^{42}*Ca,* ^{44}*Ca and* ^{48}*Ca.*

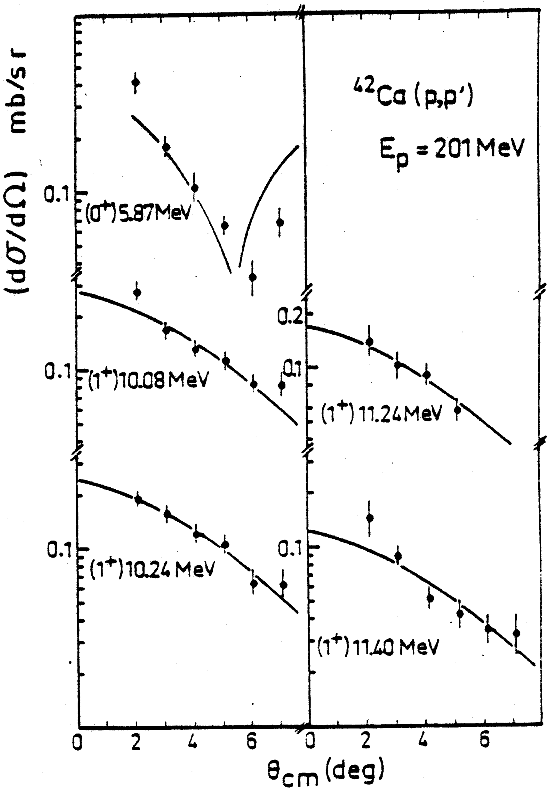


Fig. 4 - Angular distributions for ^{42}*Ca(p,p') to a known* 0^+ *state at 5.87 MeV and to four possible* 1^+ *states.*

spectra at angles as small as 2° with only moderate background from the elastic tail. Spectra measured at 3° are shown in Fig. 3. We have extracted the $0^+ \rightarrow 1^+$ cross sections in each isotope and compared them to the large-angle (e,e') data taken at Darmstadt^{14}), where the 1^+ states were first observed, and to the predictions of microscopic distorted wave impulse approximation (DWIA) calculations using detailed shell-model wave functions^{6}).

We start with ^{48}Ca. Referring back to Fig. 1, we note that the 1^+ state at 10.2 MeV is sharp, so that the cross section for exciting it can be obtained quite accurately, with little ambiguity in the background subtraction. The resulting angular distribution is shown in Fig. 2. It is very sharply forward peaked, as is characterisic of an orbital angular momentum transfer ΔL of zero at a bombarding energy of 201 MeV. $\Delta L=0$ implies that $\Delta J^{\pi}=0^+$ or 1^+. But the 0^+ possibility can be ruled out because empirically we have found for nuclei up to mass 60 that transitions to known 0^+ states have a more sharply falling angular distribution than transitions to 1^+ states. This is illustrated in Fig. 4, where the angular distributions for one known 0^+ level at 5.87 MeV and four possible 1^+ levels in ^{42}Ca are shown. These four levels have nearly the same angular distribution shape, which is the same as for the strong 10.2 MeV state in ^{48}Ca, and it is on this basis that they are identified as 1^+ candidates.

Microscopic DWIA calculations have been carried out for the 10.2 MeV state in ^{48}Ca using the codes DWBA70 and RESEDA. The results, normalized to the data, are shown as the curves in Fig. 2. Two of the curves were computed assuming a closed $\nu f_{7/2}$ shell for the ground state and a simple $\nu(f_{5/2}f_{7/2}^{-1})$ configuration for the 1^+ state (simple W-F); and one with the eight excess neutrons distributed in the full f-p shell^{6}) (full W-F). Details of the calculation are given in Ref. 9. The main result is that the simple W-F gives a quenching factor Q, defined as the ratio of experimental to calculated cross section, of 0.21 with DWBA70 and 0.24 with RESEDA. The full W-F gives Q=0.30; this is not an unexpected result because typical calculations indicate that about 20% of the 1^+ strength predicted by the independent particle model disappears due to the influence of ground-state correlations. This still leaves a large gap between theory and experiment.

Since we are dealing with an almost pure neutron excitation, quenching should appear in (p,p'), (p,n)[15] and (e,e')[14,16] reactions in comparable proportions. Only the sharp peak at 10.2 MeV is observed consistently in the different reactions. The quenching factors for excitation of this state are given in Table 1. The (p,p') values are the lowest, but they are indeed comparable to the other two.

Table 1: Quenching factors for excitation of the 10.2 MeV state of ^{48}Ca.

	(p,p')	(p,n)	(e,e')
Closed-shell wave function	0.21	0.26	0.33
Full f-p shell wave function[a]	0.30	0.35	0.47

a) Ref. 6

When we turn to the other Ca isotopes (Fig. 3), significant differences are observed between (p,p') and (e,e') results. In ^{40}Ca(p,p'), the well known 1^+ state at 10.32 MeV, first seen in (e,e'), is excited. However, an additional state seen in (p,p') at ≈12.06 MeV (indicated by an arrow in Fig. 3), which we believe is a 1^+ state, is not seen in (e,e'). Of course, if this state corresponds predominantly to a proton excitation, there might be a cancellation between the orbital and spin parts of the B(M1) operator which might suppress the transition in (e,e').

In ^{42}Ca, the 1^+ state at 11.24 MeV that is so prominent in (e,e') is seen only weakly in (p,p'). Whereas in (e,e') this state has a strength about 16% of that of the 10.2 MeV state in ^{48}Ca, the corresponding ratio in (p,p') is only about 3.3%. Moreover, there are three other possible 1^+ states excited in (p,p') to a comparable extent. One must again invoke a proton excitation component for the transitions and appeal to an orbital contribution in (e,e') to explain the lack of detailed agreement with (p,p').

The spectrum of ^{44}Ca is quite a contrast to the ^{48}Ca spectrum (Fig. 3) in that there is no dominating peak. The 1^+ strength distribution is very fragmented. But the (p,p') probe is still selective of 1^+ states. The selectivity is good enough to produce several peaks (indicated by arrows) which are relatively prominent, more so than in the (e,e') experiment.

Fig. 5 compares the observed and predicted 1^+ strength distributions for the Ca isotopes. The predictions are the results of microscopic DWIA calculations using the full f-p shell basis neutron wave functions of Ref. 6 for ^{42}Ca, ^{44}Ca and ^{48}Ca and the wave functions of B.A. Brown$^{17)}$ for ^{40}Ca. In Brown's model, the core is

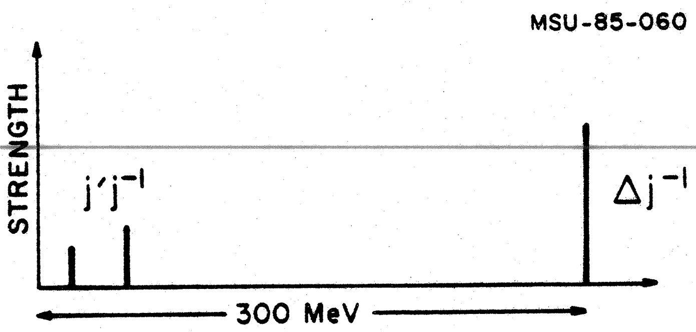


Fig. 6 - The independent particle spin-isospin strength function, including the delta state of the nucleon.

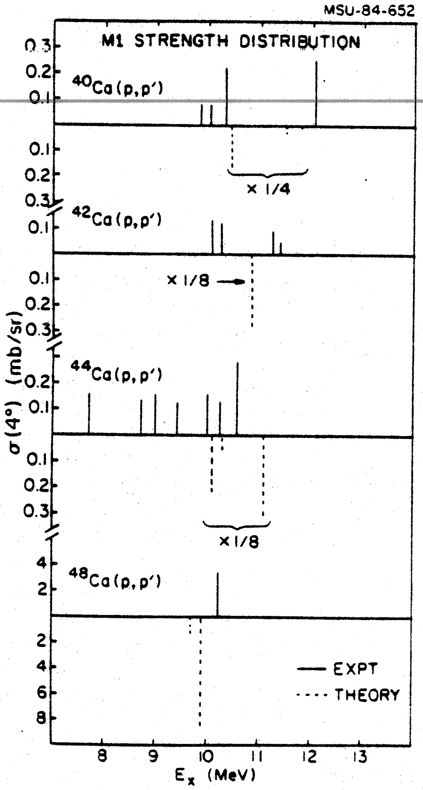


Fig. 5 - Experimental 1^+ strength distributions in the Ca(p,p') reactions compared to calculations described in the text.

^{32}S and the valence nucleons are in the $d_{3/2}$ and $f_{7/2}$ orbits. Except for ^{48}Ca, the correspondence between the observed and predicted excitation energies is poor. The ratio of the total observed strength to the total predicted strength for each nucleus, i.e. the overall quenching factor Q, is 0.77 for ^{40}Ca, 0.18 for ^{42}Ca, 0.24 for ^{44}Ca and 0.30 for ^{48}Ca. We disregard the value for ^{40}Ca on the grounds that Brown's model does not include $f_{7/2} \rightarrow f_{5/2}$ transitions, which are important. The quenching factors for the other Ca isotopes are in line with what we have come to expect from our (p,p') data over a wide range of nuclei^{10}).

3. QUENCHING OF ISOVECTOR SPIN EXCITATIONS

The quenching factors for $0^+ \rightarrow 1^+$ transitions obtained from (p,p') data depend upon model wave functions used in distorted wave calculations to make predictions of the expected strength. There are uncertainties both in these model wave functions and to a lesser extent in the reaction calculations because of uncertainties in the interaction used. There is also the possibility that some of the 1^+ strength resides in the typical "background" region and is therefore not identifiable.

All the above arguments, however, lose their force in the case of ^{48}Ca. There is little uncertainty about the wave function of the 1^+ state in ^{48}Ca, and the excitation is very concentrated in energy. This is therefore an ideal case to show that there really is less cross section than predicted. Such quenching is predominantly isovector quenching because (p,p') transitions at 200 MeV in general are predominantly isovector transitions ($V_{\sigma\tau} >> V_{\sigma}$).

Even more compelling evidence for quenching of isovector 1^+ strength comes from (p,n) studies of Gamow-Teller (GT) transitions. Unlike (p,p'), (p,n) reactions have a rigorous lower limit on the total GT strength which derives from a sum rule based on fairly general principles. The total observed GT strength is only about 60% of that expected^{2,3}). Nuclear spins appear to be quenched in other phenomena as well. The GT β-decay rate of the heavier mirror nuclei is reduced by about a factor of two18).

A number of explanations have been proposed to account for this quenching. One suggestion19) is that ordinary nuclear structure effects, such as configuration mixing between 1p-1h and 2p-2h states, might spread out the 1^+ strength in the low excitation energy region over several tens of MeV. This strength would be difficult to detect in cross section measurements since no peak structure would be apparent. A more exotic suggestion7) is that Δ-isobar admixtures enter into the nuclear wave functions in first order. This would have the effect of shifting part of the 1^+ strength to much higher excitation energy (≈300 MeV, see Fig. 6). Since all the nucleons can participate in the Δ excitation, the effect might be substantial. At present, there is much debate as to the relative importance of the two effects and whether both can explain the observed quenching.

4. QUENCHING IN ISOSCALAR $0^+ \to 1^+$ TRANSITIONS: ^{28}Si(p,p')

Since the isobar-to-nucleon coupling is isovector, the Δ-isobar mechanism is blocked from playing a significant role in isoscalar processes. Any quenching of isoscalar strength must thus be taken as strongly indicative of an important role for higher-order configuration mixing, not only in isoscalar processes but perhaps in isovector as well.

The probe of choice for exciting isoscalar transitions is (p,p'), since the alternative, (e,e'), is very much dominated by the isovector component of the M1 operator. One needs a T=0 target, so that transitions to T=0 excited states will be purely isoscalar and transitions to T=1 excited states will be purely isovector. Other considerations governing the choice of target are: (a) the isoscalar 1^+ states must be well separated from isovector 1^+ states, so that isospin mixing is minimized; and (b) good wave functions must be available for analyzing the data. The nucleus ^{28}Si satisfies all these criteria.

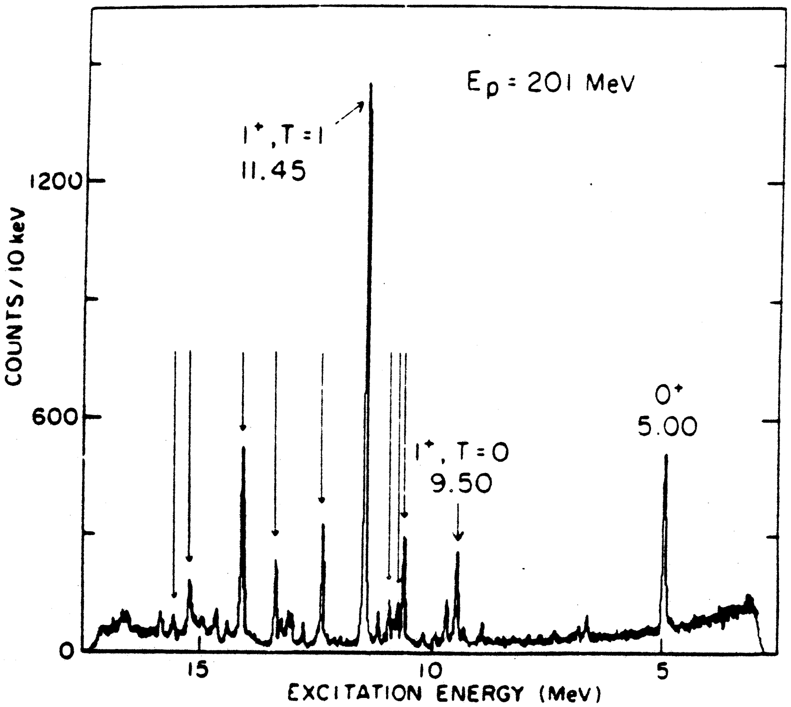


Fig.7- Spectrum of protons inelastically scattered from ^{28}Si at 3.2°.

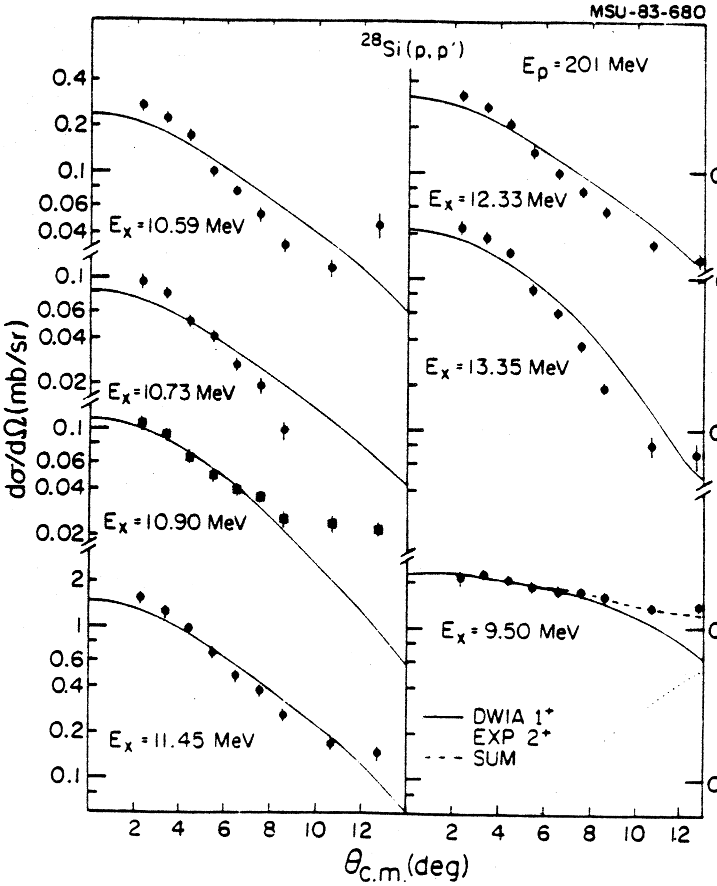


Fig.8- Angular distributions for seven 1^+ states, one (at E_x=9.50 MeV) with T=0 and the others with T=1.

A spectrum[11]) of ^{28}Si(p,p') is shown in Fig. 7. The peaks with arrows above them are T=1, 1^+ states; the peak at 9.50 MeV is a T=0, 1^+ state. Angular distributions for six of the nine observed T=1 states and for the T=0 state are shown in Fig. 8. The curves were computed with the code DWBA70 in the usual manner, with wave functions in which the twelve nucleons outside of a ^{16}O core were unrestricted in the s-d shell. Hence, a good deal of configuration mixing is already included in the theoretical cross sections. The angular distribution for the T=0 state (E_x=9.50 MeV) is much flatter than the angular distributions observed for the T=1 1^+ transitions. The DWIA calculations reproduce both the T=0 and T=1 data. The difference in the shapes can be understood qualitatively as being due to the strong, attractive $V_{\sigma\tau}$ interaction present only in the T=1 channel. The good fit obtained for the angular distribution of the 9.50 MeV state is an indication of the pure isoscalar nature of this state.

All of the calculated curves have been normalized downward in order to fit the data. The experimental and theoretical strength distributions, specifically the differential cross sections at 4°, are given in Fig. 9. It is clear that for both isoscalar and

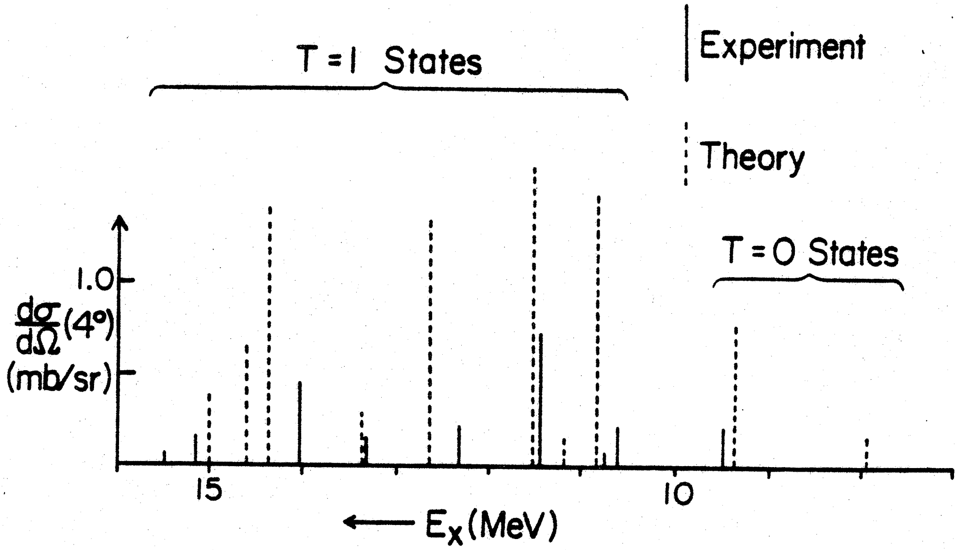


Fig. 9 - Experimental and theoretical strength distributions for 1^+ states in ^{28}Si excited by (p,p') at 201 MeV.

isovector states the experimental strength is much less than the theoretical. The ratios, that is, the quenching factors, are 0.24 for the isoscalar channel and 0.33 for the isovector channel. While the actual magnitude of this quenching is dependent on the details of the calculations we have used to extract it, the relative amounts of quenching in the two channels should be less sensitive to these details. The comparable quenching in the two channels indicates that the Δ-isobar admixture mechanism alone is not sufficient to explain the quenching. Our result, while not ruling out this mechanism in isovector transitions, points to the importance of higher-order configuration mixing as a quenching mechanism.

5. POLARIZATION TRANSFER MEASUREMENTS AT E_p=319 MeV

The polarization of the outgoing proton has been measured at LAMPF for small-angle inelastic scattering from ^{90}Zr and ^{51}V with a 319-MeV incident polarized proton beam $^{12,20)}$. The spin-flip cross section σS_{nn} (where S_{nn} is the probability that an incoming proton with spin up relative to the scattering plane goes out with spin down after the scattering) is a direct measure of spin excitations in the nucleus. In the plane wave limit, $S_{nn}=0$ for $\Delta S=0$ transitions and $=2/3$ for $\Delta S=1$ transitions. Thus S_{nn} provides a unique signature for spin-transfer reactions.

The results for ^{90}Zr (Fig. 10) show a large σS_{nn} which is approximately evenly distributed between 8 and 25 MeV excitation.

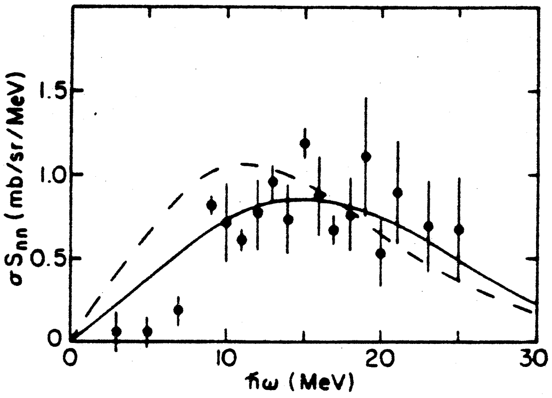


Fig. 10 - Spin-flip cross sections for $^{90}Zr(\vec{p},\vec{p}')$ at E_p = 319 MeV and θ = 3.5°. The solid (dashed) line is the prediction of Ref. 21 with (without) collective effects.

While the σ spectrum shows a definite bump at E_x=8-9 MeV (the 1^+resonance), this region is not prominent in the σS_{nn} spectrum. The observation of large spin-flip strength in the continuum above the 1^+ resonance suggests that the missing strength might well be found here, rather than in the region near 300 MeV excitation. This would be in accord with the predictions of the configuration-mixing model. Of course, while the small-angle σS_{nn} spectrum arises from low-multipole spin excitations, it is probable that not all of it corresponds to 1^+ excitation. A calculation which avoids the problem of a multipole decomposition has been carried out recently by Esbensen and Bertsch[21]). This is a parameter-free calculation of the response of a semi-infinite Fermi liquid to a spin-isospin dependent probe and gives an extremely good qualitative fit to the σS_{nn} data (Fig. 10). The model appears rough but, taken at face value, the comparison of theory and experiment indicates that there is little missing overall ΔS=1 strength and thus no room for strong effects of the Δ-isobar.

6. CONCLUDING THOUGHTS

The (p,p') reaction at 200 MeV is a good probe for exciting ΔL=0, ΔS=1 transitions. The (p,p') work has brought forth much interesting data and some open problems as well. The data do not always agree with (e,e') data, both as regards the transition strength and the number of 1^+ states excited. The difference may be due to orbital magnetic contribution in (e,e'). The quenching of strength is a general feature; typically, the observed (p,p') strength is only 25% to 30% of that predicted. Our finding of similar quenching in isoscalar and isovector transitions in ^{28}Si indicates the importance of configuration mixing. It is important not to oversimplify the problem by evaluating one or two effects independently of each other or of others, but to consider quantitatively all the related effects. Ground-state correlations, np-nh contributions, Δ-isobar admixture effects, effective nucleon-nucleon interaction, and non-one-step processes must all be included in a comprehensive treatment.

ACKNOWLEDGEMENTS

This work was partly supported by the U.S. National Science Foundation under grants PHY-80-17605, INT-81-16064 and INT-82-13242. The 201-MeV (p,p') work was carried out at Orsay in collaboration with C. Djalali, N. Marty, M. Morlet, A. Willis and J.C. Jourdain of the IPN, Orsay and G.M. Crawley and A. Galonsky of the NSCL at Michigan State University. However, any errors or lack of clarity in the present text are my own doing.

REFERENCES

1. Marty, N., Invited paper in these Proceedings.
2. "Spin Excitations in Nuclei", edited by Petrovich, F. et al. (Plenum Press, New York, 1984).
3. Proc. Intl. Symp. Highly Excited States and Nuclear Structure (Journal de Physique, Colloque C4, 1984).
4. Strictly, both ΔL=0 and ΔL=2 contribute, but at the very forward angles where the data are taken, the ΔL=2 part is negligible.
5. Bertsch, G.F. Nucl. Phys A354, 157c (1981).
6. McGrory, J.B. and Wildenthal, B.H., Phys. Lett. 103B, 173 (1981).
7. Ericson, M. et al., Phys. Lett. 45B, 19 (1973); Oset, E. and Rho, M., Phys. Rev. Lett. 42, 47 (1979); Bohr, A. and Mottelson, B.R., Phys. Lett. 100B, 10 (1981); Weise, W., Nucl. Phys. A396, 373c (1983).
8. Anantaraman, N. et al., Phys. Rev. Lett. 46, 1318 (1981).
9. Crawley, G.M. et al., Phys. Lett. 127B, 322 (1983).
10. Djalali, C. et al., Nucl. Phys. A388, 1 (1982).
11. Anantaraman, N. et al., Phys. Rev. Lett. 52, 1409 (1984).
12. Nanda, S.K. et al., Phys. Rev. Lett. 51, 1526 (1983).

13. Brown, B.A. et al., Phys. Lett. 127B, 151 (1983).

14. Steffen, W. et al., Phys. Lett. 95B, 23 (1980).

15. Osterfeld, F. et al., Phys. Rev. Lett. 49, 11 (1982).

16. Eulenberg, G. et al., Phys. Lett. 116B, 113 (1982) and private communications from W. Steffen and A. Richter.

17. Reported in Rapaport, J. et al., Nucl. Phys. A427, 332 (1984).

18. Raman, S. et al, Atomic Data and Nuclear Data Tables 21, 567 (1978).

19. Shimizu, K. et al., Nucl. Phys. A226, 282 (1974);
Bertsch, G.F. and Hamamoto, I., Phys Rev. C26, 1323 (1982).

20. Glashausser, C., preprint prepared for Comments on Nuclear and Particle Physics (1984).

21. Esbensen, H. and Bertsch, G.F., Ann. Physics 157, 255 (1984).