Proton stripping to 8^- stretched states in ^{60}Ni

R. J. Peterson, B. L. Clausen, and J. J. Kraushaar
Nuclear Physics Laboratory, Department of Physics, University of Colorado, Boulder, Colorado 80309

R. A. Lindgren* and M. A. Plum†
Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01003

W. W. Jacobs and H. Nann
Indiana University Cyclotron Facility, Bloomington, Indiana 47405

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The ^{59}Co(α,t)^{60}Ni reaction was used to populate states known to be of spin 8^- by inelastic electron scattering measurements. Single-nucleon stripping spectroscopic factors obtained by comparison to exact-finite-range distorted-wave Born approximation calculations are compared to the fractions of $M8$ single-particle strength found from electron scattering for 10 transitions. Distributions of $T=3$ 8^- strength were found to be rather similar in the two studies, with about 34% of the $T=3$ single-particle 8^- stripping strength located.

I. INTRODUCTION

Stretched states, the $1\hbar\omega$ particle-hole excitations of maximum angular momentum and unnatural parity, have been investigated in heavy nuclei mainly by electron scattering,[1,2] with some charge exchange,[3] proton, and pion scattering studies.[4] In the nickel isotopes several 8^- $(f_{7/2}^{-1}g_{9/2})$ states of isospin $T_<=T_0$ and $T_>=T_0+1$ have been located and their $M8$ transition strengths determined.[1] In an extreme single-particle picture, such strengths would be proportional to single-nucleon stripping spectroscopic factors. In a realistic view of actual nuclear configurations with more complex structure, this need not be true. The stripping reaction occurs on a single hole configuration, the target ground state, and hence does not have the coherence present for the scattering transitions. Since collective features of nuclei contain such coherences, a comparison of stripping and scattering transitions to the same simple stretched states need not agree. A simple demonstration of such effects to be expected in a Nilsson scheme has been presented.[5]

The damping of another spin excitation, the Gamow-Teller 1^+ strength, in heavy nuclei has been well documented and has raised questions concerning the role of subnucleonic degrees of freedom.[6] The influence of these damping mechanisms is expected to be less for higher spin states.[7] Nonetheless, both the isoscalar and isovector transition strengths to isolated stretched states have been observed to be damped below the simple shell model expectations.[4] Such effects could be due to surface vibrations,[8] a large tensor residual interaction,[9] an inadequate model space,[10] or to permanent deformations.[5]

Since a total of four $T=2$ and six $T=3$ 8^- states are known from electron scattering[1] (including a recent comprehensive reanalysis of the data in Ref. 1) in ^{60}Ni, this ensemble makes a good testing ground for the comparison of single-nucleon stripping and inelastic scattering excitations. The electron scattering results are listed in Table I, using harmonic oscillator radial wave functions to evaluate the single-particle form factors. Similar comparisons have been made for $A=28$ (Ref. 11) and $A=26$ (Ref. 12). The (α,t) proton stripping reaction on the $\frac{7}{2}^-$ ground state of ^{59}Co was chosen to emphasize the high spin transfers, with $l=4$ $(g_{9/2})$ stripping populating the desired 8^- states. The great selectivity of the (α,t) reaction for exciting stretched states was demonstrated in our study of the ^{25}Mg(α,t)^{26}Al reaction.[12]

II. THE EXPERIMENT

The 80.9 MeV ^{4}He beam from the Indiana University Cyclotron Facility (IUCF) was used to induce the transfer reaction on a 1.18 mg/cm^2 foil of monoisotopic ^{59}Co. The methods were identical to those of our ^{25}Mg(α,t)^{26}Al study.[12] The quadrupole-dipole-dipole-multipole (QDDM) spectrometer system in a dispersion-matched mode permitted an overall energy resolution of 90 keV. Very clearly separated triton spectra were obtained due to the high magnetic fields required. Several overlapping spectra at different magnetic field settings were obtained at each angle, and calibration spectra were obtained for each setting. This energy calibration was performed with targets of natural carbon, Mylar, and 99.92% enriched ^{58}Ni. This calibration yielded excitation energies for the ^{60}Ni final nucleus to within an accuracy of about 10 keV for the lower (20 keV for the higher) states, as listed in Table I. This permitted a very precise and systematic comparison to the electron scattering results,[1] even for peaks among the dense levels at high excitation energies. Recent reanalysis of the data in Ref. 1 finds one more 8^- state and gives different uncertainties in excitation energy than listed in that work. Details will be published separately. A sample ^{59}Co(α,t)^{60}Ni spec-

TABLE I. Results for 8^- states of ^{60}Ni from electron scattering and proton stripping are compared. States below 10 MeV are assigned $T=2$; states above 10 MeV are assigned $T=3$. Excitation energies and uncertainties for the electron scattering come from a reanalysis of the data shown in Ref. 1.

		(e,e′)					(α,t)		
E_x (MeV)	± (keV)	$M8^a$ (%)	±	$M8^b$ (%)	E_x (MeV)	± (keV)	S (%)	±	Γ (keV)
$T=2$									
7.522	15	4.82	0.12	7.23	7.550	8	5.56	0.09	36
8.433	21	2.04	0.10	3.06	8.445	11	0.45	0.03	33
8.959	42	2.85	0.09	4.28	8.994	10	1.19	0.06	79
9.172	30	2.59	0.14	3.89	9.208	10	2.06	0.11	127[c]
	Σ=	12.3	0.23	18.5		Σ=	9.3	0.15	
$T=3$									
12.333	28	1.65	0.08	4.95	12.305	20	2.37	0.15	56
12.505	39	2.88	0.09	8.64	12.515	16	5.52	0.15	103
13.908	41	4.77	0.12	14.3	13.883	16	13.0	0.72	70
14.840	40	3.12	0.14	9.36	14.817	10	7.65	0.19	64
15.499	40	2.48	0.12	7.44	15.483	19	2.67	0.14	68
16.080	40	1.86	0.11	5.58	16.110	23	3.38	0.53	87
	Σ=	16.8	0.27	50.4		Σ=	34.6	0.8	

[a]Expressed as fractions of the total $f_{7/2}^{-1}\, g_{9/2}$ single particle strength computed with harmonic oscillator wave functions from Ref. 1.
[b]Expressed as fractions of the $T=2$ or $T=3$ single particle sum strengths separately, similar to the comparison of stripping spectroscopic factors.
[c]Doublet, lower member of which yields the stated spectroscopic factor.

trum is shown in Fig. 1. As expected, many more peaks are seen in the stripping reaction than in the published electron scattering spectra which are selected to be at the momentum transfer specifically populating 8^- states. The selectivity of the (α,t) reaction to high spin states is noted by the strong $\frac{9}{2}^+$ state populated by stripping on ^{58}Ni, shown in Fig. 2.

Absolute cross sections were determined from the known target thickness, the solid angle of the spectrometer, and the integrated beam current in a Faraday cup located in the scattering chamber. A check was made on this procedure by obtaining elastic alpha particle scattering data on both the ^{59}Co and ^{58}Ni targets at angles near the 26 deg maximum. Comparisons were then made to optical model calculations, with the parameters described below. The absolute comparison of elastic data and predicted cross sections for each target was constant to within 5%, but a range of reasonable optical model parameters (as described below) yielded an uncertainty of ±10% for this method of determining absolute cross sections. We thus estimate our overall normalization uncertainty as ±10%.

Angular distributions were determined for ^{59}Co and ^{58}Ni targets from 7 to 30 deg to verify the expected $l=4$ shapes for the 8^- states. The unbound final states are expected to be sharp due to their high spins; this was checked by comparison of their peak shapes to our instrumental resolution. Table I lists the 8^- states in ^{60}Ni

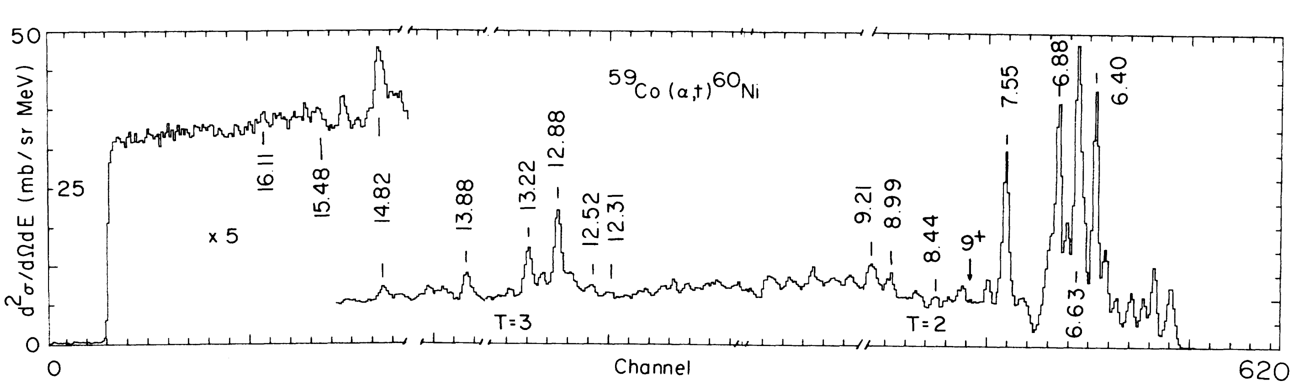

FIG. 1. A momentum spectrum for the (α,t) proton-stripping reaction on ^{59}Co is shown. Five composite spectra are normalized between runs at different magnetic field settings by the overlapping regions. All segments were taken at 7° except for the one below 7 MeV, taken at 17°. Excitation energies for the states of interest in the present work are given along with energies for other prominent states. Counts shown have been binned by four channels from the data taken and fitted.

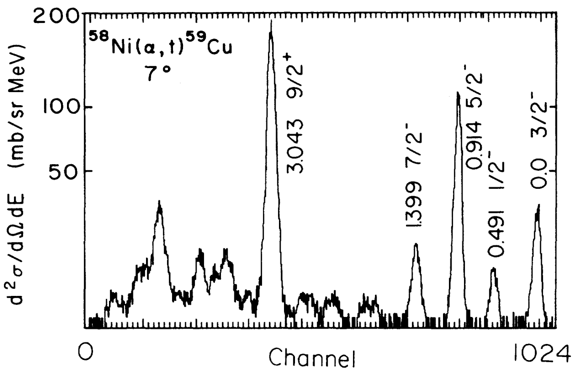

FIG. 2. A momentum spectrum for proton stripping on ^{58}Ni is shown, with the $\frac{9}{2}^+$ state selectively populated by the (α,t) reaction. Note that the vertical scale is proportional to the square root of the number of counts.

known from electron scattering[1] and also the energies and widths determined from the present experiment. A very close correlation in excitation energy is noted between the two experiments. Recent analysis of the data of Ref. 1 has found one more 6^- $T=1$ state at 16.080 MeV, exhibiting the characteristic shape for the form factor as observed for the other 8^- states reported in that work. The data will be shown in a forthcoming publication.

III. DWBA METHODS

Although the single-nucleon stripping reaction chosen for this study is not the simplest, good DWBA descriptions of $(\alpha,{}^3\text{He})$ (Refs. 13 and 14) and (α,t) (Refs. 15 and 16) reactions at high bombarding energies have been made on heavy nuclei, and careful studies of stripping to stretched states of lighter nuclei have verified these descriptions.[11,12] The present analysis for ^{60}Ni will follow closely the methods of Ref. 12.

The optical model parameters determined at the same 80 MeV beam energy on heavier targets[16] were used for the present work, including the elastic scattering normalization checks. The geometry of the potential binding the transferred proton has a great influence on the magnitude of the calculated cross sections. We follow the suggestion of Dieperink and Sick[17] to determine these parameters from magnetic elastic electron scattering from the valence nucleon. For ^{59}Co, the radius is[18] $R=r_0A^{1/3}=1.173A^{1/3}$, the diffuseness is $a=0.65$ fm, and the spin-orbit strength is 28 MeV (in the units of our analysis). In order to test the uncertainty in spectroscopic factors due to uncertainties in these parameters, calculations were also performed with the bound state parameter sets of Refs. 19–25, with results as described below.

As a test case for these calculations, we used the lowest-lying[26] $\frac{9}{2}^+$ state at 3.043 MeV in ^{59}Cu, populated cleanly, as seen in Fig. 2, in our (α,t) calibration spectra on ^{58}Ni. Although other levels known to exist near this state would not be resolved, low energy (d,n) studies have found no significant strength to these states of lower spin,[26] and a high resolution study of the $({}^3\text{He},d)$ reaction observed only the $\frac{9}{2}^+$ level.[25]

The $\frac{9}{2}^+$ angular distribution is shown in Fig. 3(a). DWBA calculations using the code DWUCK5,[27] as described below, were used to generate the curves shown, plotted with a spectroscopic factor of 0.15, as obtained to agree with DWBA results using the bound state parameter set of Ref. 18. The standard optical model parameters described below were used for this comparison. The calculated zero-degree cross sections obtained with each alternative set, relative to this one, are listed in Table II. A standard deviation of $\pm 21\%$ is obtained for the six sets, which we believe overestimates the uncertainty in our results, since some parameter sets are from global analysis of many nuclei. A similar study for $A=26$ yielded a standard deviation of $\pm 23\%$.[12] We will use only the set of Ref. 18, noting that this yields the largest DWBA cross section of any set, and hence the smallest spectroscopic factor.

Analysis of elastic electron scattering from odd-A nuclei yields larger radial parameters r_0 for $g_{9/2}$ than for $f_{7/2}$ nucleons.[18] Since we simply use the same radius for the $f_{7/2}$ proton in ^{59}Co and for the larger $g_{9/2}$ proton orbits in ^{60}Ni, we estimate that our DWBA cross sections would be decreased if we knew the proper radial parameters for these single-particle states. The sensitivity is noted in Table II. Smaller DWBA predicted cross sections would yield larger spectroscopic factors.

Optical model parameters from the literature were used with the bound state geometry of Ref. 18 to estimate the dependence of our results on different choices of optical model parameters. We also used triton parameters derived from appropriate ^{3}He results[16] and alpha parameters from the survey of Perey and Perey.[28] These parameters are listed in Table II. As shown in Fig. 3(b), the shapes of the calculated (α,t) stripping angular distribu-

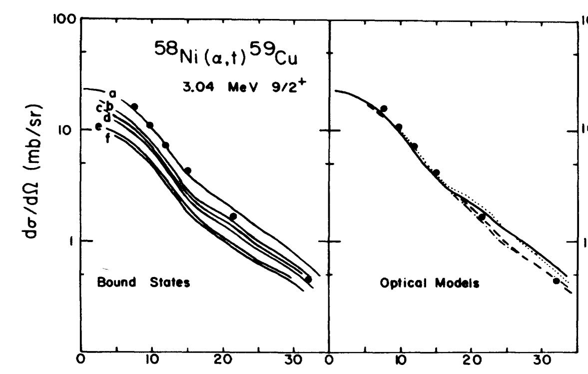

FIG. 3. Proton-stripping data to the $\frac{9}{2}^+$ state at 3.04 MeV in ^{59}Cu are compared to exact-finite-range DWBA predictions with several different potential parameter sets for the transferred nucleon, and for several sets of optical model parameters. All calculations use a spectroscopic factor of 0.15. The letters for the left diagram refer to the parameter sets listed in Table II. On the right, the solid curve uses the optical model parameters of Ref. 16, the dotted those of Ref. 28 (α) and Ref. 16 (t), the dashed those of Ref. 28 (α) and Ref. 27 (t), and the dot-dashed those of Ref. 16 (α) and Ref. 27 (t). These parameters are listed in Table II.

TABLE II. Sensitivities of (α,t) DWBA cross sections are listed for several potential parameter sets. First are listed the zero degree relative (α,t) cross sections using a variety of bound state parameters for proton stripping to the $\frac{9}{2}^+$ state at 3.04 MeV in ^{59}Cu using the optical model parameters of Ref. 16. The letters indicate the corresponding curve in Fig. 3(a). Below, optical model parameter sets are listed, used with the bound state parameters of Ref. 18 for the DWBA predictions in Fig. 3(b).

Parameters (r_0, a, λ, or V_{so})	$d\sigma/d\Omega$ (0°)	Ref.	
1.173, 0.65, $V_{so}=28$	1.00	18	a
1.11, 0.65, $V_{so}=24$	0.67	19	c
1.20, 0.65, $\lambda=25$	0.47	20	e
1.25, 0.75, $\lambda=25$	0.77	21, 25	b
1.25, 0.65, $\lambda=25$	0.61	22, 23	d
1.18, 0.665, $\lambda=25$	0.44	22, 24	f

Optical model parameters used in the DWBA calculations

	α (Ref. 16)	α (Refs. 28 and 29)	t (Ref. 16)	t (Ref. 27)	
V	−158.4	−113.1	−125.4	−142	MeV
r_0	1.32	1.325	1.18	1.20	fm
a_0	0.62	0.68	0.86	0.72	fm
W(vol)	−30.02	−22.4	−17.20	−23	MeV
r_w	1.35	1.52	1.55	1.40	fm
a_w	0.85	0.72	0.77	0.88	fm
V_{so}				−10	MeV
r_{so}				1.20	fm
a_{so}				0.72	fm
r_c	1.4	1.3	1.4	1.30	fm

tions were very similar and the magnitude of the predicted cross sections at 0° were constant within $\pm3\%$. In view of this, our results appear to have little dependence on the particular choice of optical model parameters.

The structure of the light particle in the reaction was taken into account through the exact-finite-range (EFR) method. The Fourier transform of the ^{3}He charge distribution was fit to yield $D(q)$,[13] used in the code DWUCK5. Spectroscopic factors for populating a state J_f are determined from the output of this code by

$$\frac{d\sigma}{d\Omega}(\exp)=SsC^2\frac{(2J_f+1)}{(2J_i+1)}\frac{d\sigma}{d\Omega}(\text{DWBA}) .$$

A light particle spectroscopic factor $s=2$ was used, and C^2, the isospin factors, are $\frac{5}{6}$ to $T=2$ and $\frac{1}{6}$ to $T=3$ final states of ^{60}Ni. On the ^{58}Ni target, C^2 is $\frac{2}{3}$ to the 3.043 MeV $T=\frac{1}{2}$ $\frac{9}{2}^+$ state. With these normalizations, stripping to a single empty $(f_{7/2}^{-1}g_{9/2})$ state of given spin and isospin exhausting the single particle strength would yield a unit spectroscopic factor.

An alternative to this EFR method would be to bind the proton to the mass 3 system in a radial potential, as in Ref. 11. This method, called EFR(r) in Ref. 12, yielded a computed zero degree cross section 1.09 times that for the EFR(q) method for the ^{59}Cu test case.

Many of the states populated in the ^{59}Co$(\alpha,t)^{60}$Ni reaction are above the proton separation energy. For those states, the EFR(q) methods were used as if the state were bound by 0.1 MeV and a correction was applied for the unbound effects. The zero-range (ZR) code DWUCK4 (Ref. 27) was used to compute cross sections to the unbound states treated both as a resonance and as bound by 0.1 MeV. The accuracy of this comparison between ZR and EFR(q) methods has been demonstrated for the ^{58}Ni$(^3$He$,\alpha)^{57}$Ni reaction.[13] In the present analysis the size of this correction ranged from a factor of 1.03 for the spectroscopic factors for the 12.33 MeV 8^- state to a factor of 1.19 for the 16.13 MeV 8^- state. These results are very similar to those observed for a lighter target.[12] All spectroscopic factors in Table I are from the EFR(q) method, but corrected for unbound states above 9.53 MeV.

The spectroscopic factor for the $\frac{9}{2}^+$ state of ^{59}Cu is determined to be 0.154 from the EFR(q) method using the bound state of Ref. 18, with an extreme absolute uncertainty of 11%, comprised of 10% for the normalization of the data, and 4% as half the difference between the EFR(r) and EFR(q) methods. The uncertainty due to optical model parameters is small, and the uncertainty due to the choice of bound state parameters is not included. From the $(^3$He,d) reaction at 130 MeV, a spectroscopic factor of 0.42 is determined for this $\frac{9}{2}^+$ state,[20] using the above normalization expression. If our results had been obtained with the same bound state used in Ref. 20, our spectroscopic factor would increase to 0.35 and agree quite well with the 0.42 from the $(^3$He,d) reaction.

IV. RESULTS FOR ^{60}Ni

The 8^- states found by the reanalysis of the electron scattering are listed in Table I, with associated excitation energy uncertainties given by the standard deviation of the results from several independent determinations. States found to match these excitations in the ^{59}Co(α,t)^{60}Ni reaction are also listed in Table I, with uncertainties derived from the scatter of several peak centroid determinations, added to an estimated 5 keV systematic uncertainty. Target thickness energy losses have been included, but were small for the low-lying states due to the similar ^{59}Co and ^{58}Ni target thicknesses. Thin carbon and Mylar targets were used to calibrate the higher excitations. The 8^- states are indicated in Fig. 1. Widths were estimated by subtracting in quadrature the instrumental resolution of 90 keV from the observed peak widths. Only for the 9.2 MeV and 12.5 MeV peaks was a width significantly greater than the instrumental result obtained. The shape of the 9.2 MeV peak indicates a doublet, the lower member of which is identified with the 8^- state after matching its excitation energy with the electron scattering result. The centroid of the 12.5 MeV peak in the present work matches for the 8^- state observed in electron scattering. In Table I the widths of the 8^- states are listed. For comparison, the proton single-particle width for the unbound strong 13.883 MeV peak ($S=0.13$) would be 8.2 keV. All identifications between the two reactions agree in excitation to within the stated uncertainties for the ten states, with a standard deviation of 24 keV. Angular distributions from the present work are shown in Fig. 4. In Ref. 12 it was shown that the (α,t) reaction does not distinguish clearly between angular momentum transfers. Our assignments of 8^- to the states considered are based primarily on the agreement in excitation energy with the spin-specific electron scattering results. All angular distributions are consistent with the required $l=4$ stripping pattern. In many cases, the fits are very good.

Spectroscopic factors for these 8^- states are listed in Table I, along with the single-particle $M8$ strengths from electron scattering[1] on ^{60}Ni using harmonic oscillator wave functions. The electron scattering results are listed both as the fraction of the total $M8$ strength and separately as fractions of the $T=2$ and $T=3$ single-particle strength. These latter values are to be compared to the stripping spectroscopic factors, computed also separately for $T=2$ and $T=3$ final states. For the four $T=2$ states the total single-nucleon transfer stripping strength is 9% and the total $M8$ strength is 18% of the $T=2$ single-particle value. For stripping or inelastic particle-hole excitation to an empty shell 100% would be expected in each case. In both stripping and inelastic scattering the lowest $T=2$ state is excited most strongly. There is no particular correlation between the results for the other three $T=2$ states observed in (e,e′) and (α,t).

For the six $T=3$ states the total single-nucleon stripping strength is 35% and the total $M8$ strength is 50%, again with 100% expected for stripping to the $T=3$ states of an empty shell. In both cases the states near the center of the distribution have the greatest strengths. For the electron scattering reaction, the $M8$ strength-weighted centroid energy is 14.2 ± 0.2 MeV. For the (α,t) reaction, the average $T=3$ energy weighted by the spectroscopic

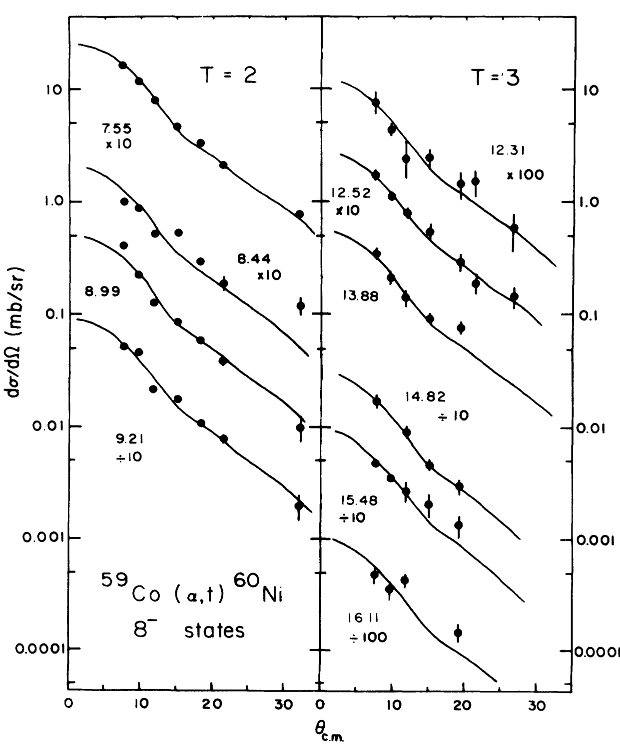

FIG. 4. Data for stripping to the 8^- $T=2$ and $T=3$ states of ^{60}Ni are compared to exact-finite-range DWBA predictions, using a momentum representation for the structure of the light particle.

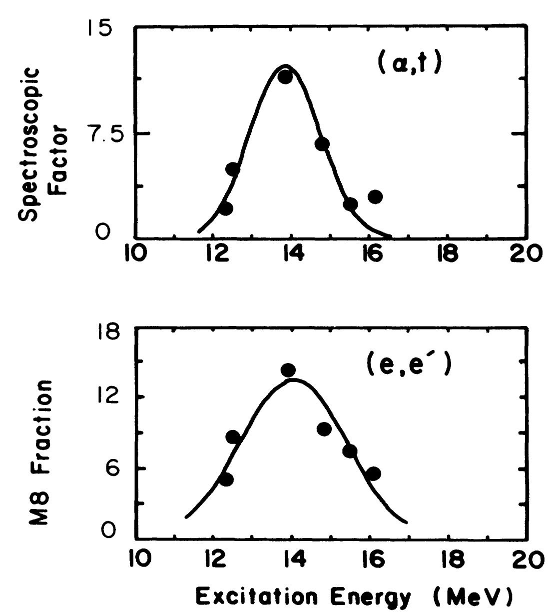

FIG. 5. Stripping and $M8$ strengths for the six 8^- $T=3$ states of ^{60}Ni are plotted as a function of excitation energy. Gaussians are fitted to the plotted points. The resulting centroids and widths are 13.86 MeV and 2.14 MeV for the (α,t) results and 14.03 MeV and 3.24 MeV for the (e,e′) results from Ref. 1. The stripping results are fractions of the $T=3$ total expected, as are the $M8$ results; these $M8$ results would be divided by three to be fractions of the total strength.

strength is 14.1±0.4 MeV. Thus, the average energies are equal within the uncertainties. If a Gaussian is fitted to the stripping spectroscopic factors the centroid is at 13.9 MeV and the width is 2.1 MeV. For the $M8$ strengths the centroid is at 14.0 MeV and the width is 3.2 MeV. The fits to both the distributions are shown as Fig. 5. Evidently, the fragmentation of the strengths as probed by the two reactions is quite similar.

V. DISCUSSION

For the first time a reasonably large sample of discrete stretched state excitations may be compared for both stripping and inelastic scattering reactions. Such comparisons have been made for ^{28}Si, with but two single 6^- states, one each of $T=0$ and $T=1$, and for $A=26$, where a range of 6^- states were compared.

The electron scattering results have been given as $M8$ fractional strengths obtained by comparison of the data to single-particle form factors computed with harmonic oscillator radial wave functions. In order to compare the data to the present stripping results, the single-particle form factors should be recomputed using isovector combinations of single nucleon radial wave functions obtained from the Woods-Saxon well used for the stripping analysis. This method, including the influence of the unbound but sharp states, has been used to reanalyze a number of stretched transitions,[31] but will not be presented here.

With oscillator wave functions, 18% of the single-particle $T=2$ $M8$ and 50% of the $T=3$ $M8$ strength were located in ^{60}Ni.[1] For the stripping results, these values are, respectively, 9% and 35%, with an absolute accuracy estimated as ±24% of those fractions, including experimental and theoretical uncertainties. The single lowest $\frac{9}{2}^+$ single proton stripping transition to ^{59}Cu was found to exhaust 15% of the stripping $T=\frac{1}{2}$ strength.

Open shell random-phase approximation (RPA) calculations for 8^- states in ^{60}Ni yield but one $T=3$ state at 14.44 MeV.[32] The spectroscopic center of gravity for the isovector $T=3$ electron scattering strength is found at 14.16 MeV, in good agreement with the prediction, but exhausts 50% of the $T=3$ strength, whereas 96% is predicted.[32]

Two $T=2$ 8^- states are predicted,[32] with the lower showing much greater $M8$ strength. However, both of the predicted 8^- states are higher in excitation than any $T=2$ peak seen in the electron scattering, and the lowest observed state is not so strongly emphasized as predicted.

Many more 8^- states are located than are predicted, with a particularly symmetric distribution for the $T=3$ strength. In Fig. 5 the $T=3$ $M8$ strengths (as percentages of the total $T=3$ strength) and the proton spectroscopic factors (also as percentages of the $T=3$ strength) are plotted and fit by Gaussian distributions. These fits indicate some statistical distribution of the transition strengths, spread from one fundamental state among several physical states. Among the means to spread simple single-particle modes are the couplings to surface vibrations, as discussed in Ref. 8. In the adiabatic limit of a low frequency 2^+ vibration coupled to a single-particle state, the width of the single-particle strength has been estimated.[8] With explicit evaluation for the 8^- states and using an amplitude for the first vibrational[29] state of $\beta_2=0.21$,[33] the expression yields a spreading parameter for the Gaussian of $\sigma=3.0$ MeV, very similar to that found for both $M8$ and stripping strengths. Similar distributions of observed single-particle states have been summarized in Ref. 8, but these experimental results have been for unresolved bumps in the spectra, not for discrete states of known spin and isospin as in the present case.

A more comprehensive calculation including the mixing of all phonon modes below 5 MeV in excitation spreads the 8^- strength into two clusters,[34] the upper of which appears much as the data in Fig. 5. This calculation finds that the states with $T=2$ and $T=3$ are at very similar excitations, leading to expectations of severe isospin mixing.

For the $T=2$ states, two 8^- states have been predicted[32] and four are observed with the lowest the strongest in both electron scattering and single-proton stripping. This result will be analyzed in a particular collective model based on the Nilsson scheme.[5] The strongest 8^- state will have a projection $K=8$ on the symmetry axis, with a predicted $M8$ electron scattering strength of $\frac{2}{17}$ (or 12%) of the single particle value; experimentally all $T=2$ states total this strength. The $K=8$ single-proton stripping strength, based on a $K_h=\frac{7}{2}$ ground state, is $\frac{100}{119}$ or 84% of the $T=2$ strength, whereas the strongest single $T=2$ stripping transition is found to exhaust but 5.6% of that strength.

Counting up the Nilsson coefficients[35] for $\beta=+0.2$, as measured for the permanent deformation of ^{59}Co,[30] for ^{60}Ni for $f_{7/2}$ occupied states only, shows that 70% of that proton shell is full and available for particle-hole excitations. Ninety-six percent of the ground state $f_{7/2}$ proton occupation is available in a shell model calculation.[36] In either case, such lack of closure is not enough to account for the small fraction of 18% of the $T=2$ strength observed in the experimental results for $M8$ electron scattering.

The Nilsson scheme with $K=8$ states at low excitations requires a negative deformation, not as found experimentally for ^{59}Co.[30] A positive deformation requires the low-K Nilsson configurations to be low in the spectrum, and these have very small amplitudes for scattering or stripping reactions. Some further concentration into the lower 8^- states can be achieved with the Coriolis interaction,[37] but no simple Nilsson scheme can account for our results.

We observe a smaller fraction of the single-proton stripping sum rule strength to the $T=2$ (9%) than to the $T=3$ (35%) states. If the single-particle $T_<$ strength is thus especially damped, scattering strength to these states must also be damped more heavily than that to $T_>$ states. This may account for the greater damping of isoscalar 8^- strength than that for isovector transitions observed in pion scattering on ^{54}Fe,[4] since all isoscalar strength must be in the $T_<$ states. No isospin analysis of the $T_<$ states in ^{60}Ni can be performed on the basis of only the electron scattering results.

A fragmented hole state spectrum would lead to a distribution of 8^- strength. The neutron $T=\frac{5}{2}$ hole state in ^{59} Ni has been measured to be split into several pieces, but only by a 13 keV spreading width.[38] Such a small spread in 8^- strength would not even be observed in the present (α,t) experiment.

The $T=\frac{3}{2}$ neutron hole state of ^{59}Ni is observed to be split into 11 states spread over about three MeV of excitation.[39] The $T=\frac{5}{2}$ proton hole state of ^{59}Co is much more concentrated into the ground state.[40] In Fig. 5, or from Table I, the $T=3$ proton spectroscopic factors are weaker than the $T=3$ $M8$ electron scattering strengths by a factor of about 0.68. Magnetic elastic electron scattering on the $\frac{7}{2}^-$ ground state of ^{59}Co finds that state to be less than a perfect $f_{7/2}$ proton hole by a factor of 0.48 ± 0.04, using $\alpha_8=0.69(3)$ from Table X of Ref. 18. The damping of the $f_{7/2}^{-1}$ $g_{9/2}$ stripping strength based on that ground state must be less by this factor than the electron scattering strength based on the entire $f_{7/2}$ hole state spectrum. This is much as observed.

High spin states of ^{60}Ni have been located by the ^{58}Ni(α,2pγ)^{60}Ni reaction,[41], but no 8^- levels were found. Since the lowest 9^- state was found at 6.811 MeV, it is likely that an 8^- level exists below those found by electron scattering, sensitive only to isovector excitations, not collective rotational modes. As seen in Fig. 1, the (α,t) reaction gives no measurable yield to the known 6.811 MeV 9^- state, indicating little contribution from $3\hbar\omega$ excitations. Similarly, we do not excite the 8.044 MeV 9^+ state or the 8^+ state at 6.460 MeV, showing no low-lying $h_{11/2}$ stripping to these collective states. Since the low-lying 5^-, 6^-, 7^-, and 8^- states in somewhat heavier targets have been shown to be due to two-quasiparticle configurations,[42] the known[41] 5^-, 6^-, and 7^- states of ^{60}Ni should be excited in our reaction, but were unfortunately not in the spectral regions we examined.

VI. CONCLUSIONS

We conclude that the simplest schemes to account for the distribution of 8^- stretched spin modes in ^{60}Ni are inadequate. Many similarities between coherent inelastic electron scattering and incoherent proton stripping data are found. Both reactions find less than the expected strength, compared either to the single-particle model or more realistic RPA calculations. Coupling to a surface phonon does account for the shape of the $T=3$ distribution, but predicts nothing like the distribution of $T=2$ strengths. The absolute strengths for electron scattering and proton stripping seem to be related by the hole nature of the ^{59}Co ground state. It is rather disturbing that for an experimentally favorable case we are able to locate so little of the strength of what should be a simple and important nuclear mode. Since we locate only 15% of the strength expected for the ^{59}Cu "single particle " $\frac{9}{2}^+$ $T_<$ state, the fragmentation of ^{60}Ni $T_<$ 8^- strength may be related to this shortage, but we find only 9% of such 8^- strength. Even this empirical particle fragmentation is not enough to match our results. A state-by-state comparison of stripping and electron scattering strengths shows great scatter for the $T=2$ peaks. Since the electron scattering measures only the isovector strength and the stripping reaction only the proton strength, any difference between the distribution of isoscalar and isovector strengths will influence the reactions differently. Pion inelastic scattering data are awaited to complete this study.

A comparison of electron scattering and stripping to 8^- states of ^{52}Cr is presently being carried out. For a more nearly spherical nucleus such as ^{52}Cr we anticipate some simplifications compared to ^{60}Ni.

The two big peaks seen in the spectrum of Fig. 1 at 12.88 and 13.22 MeV are not identified as 8^- states in electron scattering.[1] A future paper will show both the (α,t) and electron scattering results for these states.

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*Present address: Physics Department, University of Virginia, Charlottesville, VA 22901.

†Present address: Los Alamos National Laboratory, Los Alamos, NM 87545.

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