Title

5 Ni(p, 3He) 56Co AND (p,t)56Ni REACTIONS AT 45 MeV.

Authors

Bruge, G.
Leonard, R.F.

Publication Date

1970-06-01

Submitted to Physical Review

UCRL-19915
Preprint
c. 2

^{58}Ni(p, ^{3}He)^{56}Co AND (p, t)^{56}Ni REACTIONS AT 45 MeV

G. Bruge and R. F. Leonard

June 1970

AEC Contract No. W-7405-eng-48

UCRL-19915

LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

34

DISCLAIMER

^{58}Ni(p, ^{3}He)^{56}Co AND (p,t)^{56}Ni REACTIONS AT 45 MeV

G. Bruge[†] and R. F. Leonard[††]

Lawrence Radiation Laboratory
University of California
Berkeley, California 94720

June 1970

ABSTRACT

The reactions ^{58}Ni(p, ^{3}He) and ^{58}Ni(p,t) have been studied at a proton energy of 45 MeV. An average energy resolution of 45 keV has been achieved. Angular distributions have been obtained for 26 levels of ^{56}Co and 20 states of ^{56}Ni. The experimental results have been compared with DWBA calculations using spectroscopic amplitudes given by a microscopic calculation.

I. INTRODUCTION

In the nuclear shell model both ^{56}Co and ^{56}Ni may be thought of as having relatively simple structures. In ^{56}Ni (Z = N = 28) both neutrons and protons have just filled the $1f_{7/2}$ shell, while ^{56}Co may be regarded as a ^{56}Ni core plus a single $1f_{7/2}$ proton hole and 1 neutron outside that shell. Consequently, microscopic calculations of wave functions describing the states of these nuclei are available for both.[1,2,3] Experimentally, however, neither of these nuclei may be studied by the familiar methods of inelastic scattering or single-particle transfer reactions. Consequently the only available results have been obtained from decay experiments,[4,5,6,7,8] two particle transfer, or charge exchange reactions. ^{56}Co, for example has been investigated by means of the $^{54}Fe(^3He, p)^{56}Co$ reaction[9,10,11,12] at low energy; $^{58}Ni(d, \alpha)$,[9,10,13,14,15] $^{54}Fe(\alpha, d)$[16] and $^{56}Fe(He^3, t)$.[17,18,19,20] To date, however, no study of ^{56}Co with the (p, ^3He) reaction has been reported, mainly due to the large negative Q value for the reaction (-11.839 MeV).[21] The previous experiments have yielded considerable information on the structure of low-lying ^{56}Co states and have located some two-particle, two-hole states, including the T = 2 isobaric analogs of the ground and first excited (2^+) states of ^{56}Fe.[9,10,20]

The nature of these two-particle, two-hole states has also been qualitatively confirmed by the $^{56}Fe(^3He, t)$ reaction, which is particularly well suited, as a result of the ^{56}Fe structure, for their formation. In this same study,[18,19] however, a number of states were observed whose angular distributions do not display the expected shapes. This failure may be due to a poor description of either the nuclear structure or the reaction mechanism. In either case a study of the (p, ^3He) reaction should be helpful in understanding more ^{56}Co states.

The ^{56}Ni nucleus is more difficult to study. To date, only two kinds of experiments have been performed: $^{54}Fe(He^3, n)$,[11] which measured the ^{56}Ni mass and excitation energies for three excited states; and three previous $^{58}Ni(p,t)$[22,23,24] experiments. The last of these, by Davies _et al_.[24] had an energy resolution of 70 keV and identified a number of states up to excitation energies of 8.5 MeV including the T = 1 isobaric analogs of several ^{56}Co levels. In view of the better energy resolution obtainable here, it seemed worthwhile to restudy the (p,t) reaction. In addition, since it was done simultaneously with the (p, ^3He) reaction, a comparison of the cross sections for formation of pairs of isobaric analog levels is possible.

Finally, there are now available for both nuclei new microscopic wave functions.[3] They will be compared to the experimental results. The sensitivity of the calculated angular distributions to the wave functions used will provide a more quantitative test for these wave functions.

II. EXPERIMENTAL

The 45-MeV proton beam of the 88-inch Berkeley cyclotron has been used to bombard a self supporting ^{58}Ni foil. The target was isotopically enriched (> 99%) and its thickness was 200 ∓ 50 μg/cm^2. Outgoing tritons and ^{3}He's were detected by means of two solid state silicon E-ΔE telescopes (ΔE = 250 μm, E = 3 mm), coupled to a Goulding particle identifier. Data were taken between 14° and 70° cm. The cross section errors which will be indicated in tables or graphs are only statistical. An error of approximately 25% in the absolute cross sections results from the uncertainty in target thickness. Energy calibration of the system was accomplished by means of the ground state Q-values for ^{58}Ni(p,t) and ^{58}Ni(p, ^{3}He) (Ref. 21) together with Q-values for the same reactions on ^{16}O (Ref. 21) which was present as a target contaminant.

III. RESULTS

A. ^{56}Co

Figure 1 displays an experimental spectrum. The overall resolution is 50 ± 5 keV. Angular distributions have been measured for 26 ^{3}He groups corresponding to levels in ^{56}Co up to 5.2 MeV excitation energy. In a first step, using either empirical curves relative to previously known levels in ^{56}Co, or rough DWBA calculations, twenty-one of these can be classified according to the strongest component of the angular momentum (L) of the transferred nucleon pair. Four L = 0 transitions have been observed, eleven L = 2, five L = 4, and one L = 6. The angular distributions are shown in Fig. 2. Table I summarizes the excitation energies and L-values measured in the present experiment and compares them with other available experimental results.

B. ^{56}Ni

Triton groups corresponding to 24 levels of ^{56}Ni have been detected. The highest excitation energy observed was 8.896 MeV. A typical triton energy spectrum is shown in Fig. 3. Angular distributions were measured for 20 states. For 17 of these, L values have been confirmed or assigned. A summary of the energy levels, spins, parities, and total cross sections (integrated from 14° to 70°) is given in Table II. Also listed there are the results of the experiment of Davies _et al_.[24] All of the angular distributions measured in the present experiment are shown in Fig. 4.

IV. CROSS SECTION CALCULATIONS

A. General Formalism

The general formalism for two-particle transfer reactions has been extensively described.[25,26] Assuming a spin-isospin dependent, zero-range interaction, the two particle transfer cross section can be written:

$$\frac{d\sigma}{d\Omega} = \frac{\mu_A\mu_b}{(2\pi\hbar^2)^2} \frac{k_b}{k_a} \left(\frac{2s_b+1}{2s_a+1}\right) \sum_{JM\sigma_A\sigma_b} \left| \sum_{LST\Lambda} b_{ST} \, (T_B\tau_B T\tau | T_A\tau_A) D(S,T) \right.$$

$$\left. \times \sum_N g_N(LSJT) \; B_{L\Lambda}(\theta) \right|^2 , \qquad (1)$$

where

$$g_N(LSJT) = \sum_{\substack{n_1\ell_1 j_1 \\ n_2\ell_2 j_2}} S_{AB}{}^{1/2}(n_1\ell_1 j_1; n_2\ell_2 j_2) \; G_N(LSJT) \quad , \qquad (2)$$

where $b_{ST}{}^2$ is essentially a spectroscopic factor for the light particle. Also $D(S,T)$ is a spin-isospin exchange term introduced by Hardy and Towner.[27] It can be deduced from the force mixture which is used. In the following calculations we have taken the value 0.42 for the ratio R

$$R = \left| \frac{D(1,0)}{D(0,1)} \right|^2 \quad . \qquad (3)$$

This corresponds to the force mixture of Gillet and Vinh-Mau for ^{16}O.[28]

All the quantum numbers are defined as

$J(M)$ = total angular momentum of the final nuclear state (and its z component).

σ_a, σ_b = z component of spin of incoming and outgoing particles respectively.

$\left.\begin{matrix} L(\Lambda) \\ S \\ T(\tau) \end{matrix}\right\}$ = orbital angular momentum, total spin, and isospin of the center of mass of the transferred nucleon pair (and their Z components).

N = principal quantum number of the center of mass motion of the nucleon pair.

$[n_1\ell_1j_1],[n_2\ell_2j_2]$ = quantum numbers of nuclear shell from which nucleons 1 and 2 are picked up.

The spectroscopic amplitude $S_{AB}^{1/2}$ expresses the parentage of the target nucleus A, based on the final nucleus B plus 2 nucleons in the shells $[n_1\ell_1j_1]$, $[n_2\ell_2j_2]$, and is exactly the quantity defined by Towner and Hardy.[26] The quantities $G_N(LSJT)$ are the structure amplitudes tabulated by Glendenning in Refs. 29 and 30. $B_{L\Lambda}(\theta)$ includes geometrical factors and the radial integral of the form factor.

B. Selection Rules

Assuming that in both ^{3}He and t, the three nucleons have a relative angular momentum 0, one finds $S + T = 1$ and $\pi_i \pi_f = (-)^L$.

The selection rules can be summarized as follows for a zero spin target:

1. <u>$(p, {}^3He)$ reaction</u>. For the transitions to the positive parity states in ^{56}Co the L values will be even, thus in the general case where the two particles are transferred from different shells:

$$\text{if J is even, } J = L \begin{cases} S = 0 & T = 1 \\ S = 1 & T = 0 \end{cases}$$

$$\text{if J is odd, } S = 1,\ T = 0 \text{ and } L = J \mp 1 \quad ,$$

when both of the particles are from the same shell, J + S must be even and for J even only the (S = 0, T = 1) possibility remains.

2. <u>(p,t) reaction</u>. The isospin of the removed neutron pair is T = 1. Thus the selection rules are:

$$L = J \text{ and } \pi_i\ \pi_f = (-)^L \quad .$$

Under these conditions the (p,t) reaction allows the observation of only natural parity states.

C. Calculation of the Cross Section

The calculation of the cross section has been carried out using Glendenning's values for the structure factors G,[29,30] and the computer code DWUCK[31] modified by J. C. Hardy to perform two-nucleon transfer calculations, including coherence effects caused by spin-orbit terms in the optical potentials.

D. Optical Potentials

Several optical potentials have been tested in each of the particle channels. Three different proton potentials have been used, two triton, and two ^3He. These are listed in Table III. Various combinations of proton-triton and proton-^3He potentials have been tested on the (p,t) experiment to determine which gave the best fit to the ground state angular distribution. The best fit was obtained using set 1 for the protons and set 6 for the tritons. The use of potential 5 for the tritons and ^3He's gave the same shapes and the same relative strengths for all states, although calculated absolute cross sections were changed. Potentials 4 and 7 gave significantly poorer fits to experimental angular distributions. The results presented here used the same potentials for both the (p,t) and (p, ^3He) reactions.

E. Spectroscopic Factors and Shell Model Wave Functions

It can be seen in Eq. (1) that the expression for the cross section involves a coherent sum over various single particle components ($n\ell j$). Consequently it is impossible, given experimental cross sections, to determine spectroscopic amplitudes. However, this also implies that the calculation of two-particle transfer cross sections provides a test of not only the magnitude but the signs of various components of any theoretical wave function.

For the present work, wave functions and two-particle spectroscopic factors have been calculated by McGrory[3] and used for the ^{58}Ni ground state, and all the states of ^{56}Co and ^{56}Ni. These were calculated assuming an inert ^{40}Ca core and configurations involving up to 2 holes in the $1f_{7/2}$ shell, with the remaining nucleons distributed over the $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ shells. Single particle energies used were those which best reproduced the ^{57}Co spectrum.[36] Matrix elements were calculated using the interaction of Kuo and Brown.[37]

The states which resulted from this calculation are shown and compared with experiment in Figs. 5 and 6. It is clear that an unambiguous comparison of theory with experiment based on excitation energy alone is not possible. In addition, determinations based on the shape of the angular distributions are also sometimes ambiguous. For instance, we have observed in ^{56}Co eleven L = 2 transitions, which may correspond to either 2^+ or 3^+ states. The microscopic calculations do not predict very dramatic changes in the angular distributions between 2^+ and 3^+, as shown in Fig. 7. Consequently, the criteria adopted for this comparison are based on first, the shape (dominant L-value) of the cross section; second, the order in excitation energy; and third the strength of the calculated cross section compared to experiment, expressed in terms of the normalization factor N, where

$$N = \sigma(\text{experimental})/\sigma(\text{theoretical}).$$

V. DISCUSSION

A. ^{56}Co

Below 2.5 MeV, the level density of ^{56}Co is such that the present experiment should be able to resolve most states. That this was accomplished is indicated by the excellent agreement of excitation energies with other high resolution experiments. Above 2.5 MeV, however, the level density increases so that, except for the selectivity of the reaction mechanism, very few single states should be resolved with our resolution. From this point of view a comparison of various experimental results will be given.

Within simple shell model considerations, the lowest lying states of ^{56}Co are expected to be 1 particle-1 hole states of the form

$$[(\pi f_{7/2})^{-1}(\nu p_{3/2})]_{2,3,4,5}\ ,\ [(\pi f_{7/2})^{-1}(\nu p_{1/2})]_{3,4}\ ,\ [(\pi f_{7/2})^{-1}(\nu f_{5/2})]_{1,2,3,4,5,6}.$$

Vervier's wave functions[1] indicate that these levels should lie below approximately 3.5 MeV.

The 2 particle-2 hole states should begin to appear at higher energies, the lowest group being of the configuration

$$[(\pi f_{7/2})^{-2}(\pi p_{3/2})(\nu p_{3/2})]^{T=1}_{0\cdots 3}\ ,$$

the centroid for this configuration is expected at approximately 2.5 MeV.[10] 2 particle-2 hole levels may be pictured in terms of a "weak-coupling" model used by Arima <u>et al</u>.[38] for ^{16}O and Sherr <u>et al</u>. for ^{42}Sc.[39] Let us adopt the following notations to represent a 2 particle-2 hole state;

$$\begin{array}{c|l} \alpha & \beta\ (T_p,\ J_p) \\ \hline \gamma & \delta\ (T_h,\ J_h) \end{array}$$

where α and β represent the number of protons and neutrons respectively, outside a closed $f_{7/2}$ shell; γ and δ the number of protons and neutrons in the $f_{7/2}$ shell; $T_{p(h)}$ and $J_{p(h)}$ represent the total isospin and spin of the particles (holes). Any two particle-2 hole state of ^{56}Co may then be represented by the following configurations:

$$|1\rangle = \begin{array}{c|c} 1 & 1 \\ \hline 6 & 8 \end{array} \begin{matrix} T_p = 0 \\ T_h = 1 \end{matrix}$$

$$|2\rangle = \begin{array}{c|c} & 2 \\ \hline 7 & 7 \end{array} \begin{matrix} T_p = 1 \\ T_h = 0 \end{matrix}$$

$$|3\rangle = \{ (\frac{1}{\sqrt{2}} \begin{array}{c|c} & 2 \\ \hline 7 & 7 \end{array} - \frac{1}{\sqrt{2}} \begin{array}{c|c} 1 & 1 \\ \hline 6 & 8 \end{array}) \begin{matrix} T_p = 1 \\ T_h = 1 \end{matrix} \}_{T = 1}$$

$$|4\rangle = \{ (\frac{1}{\sqrt{2}} \begin{array}{c|c} & 2 \\ \hline 7 & 7 \end{array} + \frac{1}{\sqrt{2}} \begin{array}{c|c} 1 & 1 \\ \hline 6 & 8 \end{array}) \begin{matrix} T_p = 1 \\ T_h = 1 \end{matrix} \}_{T = 2} \quad .$$

Each of these configurations, however, is similar to a known nucleus. The outer particles in $|1\rangle$ for example can exist in states which are already known, namely the $(T = 0, J = 1,3)$ states of ^{58}Cu and similarly the holes in $|1\rangle$ form the $(T = 1, J = 0,2,4,6)$ levels of ^{54}Fe. Assuming a J_p, J_h, J independent particle-hole interaction, one may construct a series of $T = 1$ states of ^{56}Co by coupling all the $T = 0$ $(J = 1,3)$ states of ^{58}Cu (Ref. 40) to the $T = 1$, $J = 0,2,4,6$ states of ^{54}Fe (Ref. 41). Using Zamick's formulation,[42] the energies for levels of configuration $|1\rangle$ corresponding to the coupling of the ^{58}Cu 1^+ and 3^+ states to the ^{54}Fe ground state will be given by:

$$E_{1^+,3^+} = M(^{58}\mathrm{Cu}_{1^+,3^+}) - M(^{56}\mathrm{Co}) + M(^{54}\mathrm{Fe}) - M(^{56}\mathrm{Ni}) - 4a + 2c \quad .$$

This energy will be compared to that of the previously known 0^+ analog (3.587) and antianalog (1.444 MeV) states which are:

$$E(0^+)_{T=1,2} = \frac{1}{2}\{M(^{58}Cu)_{0+} - M(^{56}Co) + M(^{54}Fe) - M(^{56}Ni) + 2c\}$$

$$+ \frac{1}{2}\{M(^{58}Ni) - M(^{56}Co) + M(^{54}Co) - M(^{56}Ni)\} - 4a \mp b \quad ,$$

where a is the center of gravity of particle-hole states, c is the Coulomb particle hole energy and b characterizes the separation of the T = 1 and T = 2 centers of gravity.[42] The sign + refers to the analog state. In ^{56}Co the difference of the energies of the (T = 1) and (T = 2) 0^+ states equals 2b and yields b = 1.07 MeV. This value is smaller than usual.[42] The Coulomb energy c will be taken as -0.4 MeV.[42] Taking as reference the 0^+ (T = 1) 1.444 MeV state we can eliminate the a parameter. This yields finally for the 1^+ and 3^+ states of configuration $|1\rangle$ predicted energies which are 2.17 and 2.62 MeV respectively. In the same way, states of the form $|2\rangle$, $|3\rangle$, and $|4\rangle$ can be constructed by coupling the known levels of ^{58}Ni (Ref. 8) and ^{54}Co (Ref. 43), or ^{58}Cu (Ref. 40) and ^{54}Fe (Ref. 41), with the proper isospin. In particular 7^+ and 1^+ levels of configuration $|2\rangle$ can be predicted at 2.86 and 3.78 MeV, respectively.

One should expect to see only a few of these states, since most of them are capable of mixing with some nearby level. In particular, these 0^+, 1^+, 3^+, 7^+ and second 1^+ states might be relatively pure. Our discussion in terms of this model will be restricted to these levels.

Examination of the configurations shows immediately that states of the form $|1\rangle$ will be preferentially excited by (^3He,p) reactions, $|2\rangle$ will be enhanced in (p, ^3He) reactions, while $|3\rangle$ and $|4\rangle$ should be equally strong in both reactions.

To compare the observed cross section with theory in a quantitative way, we shall use McGrory's wave functions and DWBA as outlined in Section IV. It is necessary before proceeding, however, to point out several remarks on this calculation. First, at the proton energy available (E_p = 45 MeV) it is quite possible to observe pickup of nucleons from deeper shells, exciting states such as $[(d_{3/2})^{-2}(p_{3/2})^2]$. These configurations are not included in McGrory's calculations. Secondly, since the absolute value of the (p, ^{3}He) cross section is not calculated, agreement with observed strengths will be judged as reasonable if the normalization constant N = σ(experiment)/σ(theoretical) agrees within a factor of two with an average normalization $\langle N \rangle$ = 37, determined from the four states which are assumed to be well known as described by the $[(\pi f_{7/2})^{-1}(\nu p_{3/2})]_{2^+3^+4^+5^+}$ configuration. These levels are the ground state (4^+), 0.166 MeV (3^+), 0.578 MeV (5^+) and 1.001 MeV (2^+) levels. The calculated wave functions for these states include effectively a strong component of this configuration. There is, however, some ambiguity for the 1.001 MeV level since the 0.961 MeV state also displays an L = 2 angular distribution and has nearly the same strength. Assignment of $J^\pi = 2^+$ to the 1.001 MeV state is based on a better agreement with the shape of the angular distribution. A summary of the experimental results compared to the McGrory calculation, is presented in Table IV. The 0.961 MeV state is tentatively assigned as the second level with $J^\pi = 3^+$, although the rather large normalization makes this questionable. Two weak states, principally L = 4 are seen at 0.84 and 1.106 MeV. In (d,α) experiments[15] a state was seen at 0.824 MeV with L = 4 and another at 1.107 MeV with L = 2 + 4. Both of these states give rather poor results when compared with either 5_2^+ or 4_2^+ states of the McGrory's calculation.

The transition to the 1.444 MeV state is principally $L = 0$. Its spin has previously[6,7,10,18] been limited to be 1^- or 0^+, so that the assignment $J^\pi = 0^+$, $T = 1$ may now be made. This state would correspond to a one phonon pairing vibration state taking ^{56}Ni ground state as reference[44]. As expected for a 0^+, the 1.444 MeV level is not excited in (d,α), but is reasonably populated in both $(^3He, p)$ and $(p, ^3He)$, as shown in Fig. 8, which gives a comparison of the integrated cross sections for these two reactions, as well as for the $^{56}Fe(^3He, t)^{56}Co$ reaction at 30°. The relative strength of the 1.444 MeV state in the two reactions is a further indication that this level is the 0^+ $T = 1$ state with the configuration $|3\rangle$ in the weak-coupling model. Also, as predicted for such a state, it is very weakly excited in $(^3He, t)$ reactions[18,19] where in fact it exhibits an angular distribution of $L = 1$ shape.[18] This is not surprising since several known 0^+ anti-analog states[45] exhibit angular distributions with $L = 1$ shapes. The cross section predicted for this state (0_1^+) by McGrory is somewhat small.

The 1^+ nature of the 1.714 MeV level has been previously established. It furnishes an example of well-mixed L values (0,2) for an unnatural parity state. It is also assigned 1^+ in the most recent (d,α) experiment.[15] The fact that this state is strongly excited in the $(^3He, p)$ experiments suggests that it might correspond to the weak-coupling 1^+ of configuration $|1\rangle$ predicted at 2.17 MeV. However, this state is also populated in $(p, ^3He)$ indicating that it also contains some admixture of other states, such as the 1^+ of form $|2\rangle$ predicted at 3.78 MeV. McGrory's wave function for this state (1_1^+) contains many terms, the strongest of which are types $|1\rangle$ and $|3\rangle$. Unfortunately, the calculated cross section is somewhat small, indicating perhaps that a stronger type $|2\rangle$ component is needed.

We have measured three L = 2 angular distributions (1.924, 2.050 and 2.220 MeV) in agreement with previous experiments. The 1.924 MeV state is observed in both (He^3, p) and (p, ^3He) experiments, it has been proposed as the 2p-2h antianalog 3^+ state.[10] Angular distributions calculated using McGrory's wave functions suggest that these three states should be 3^+_3, 2^+_2, and 2^+_3 respectively.

The 2.271 MeV level is the only L = 6 transition observed in the present experiment. Selection rules allow J = 5, 6, 7. The state has also been reported as strongly excited by Scheider and Daehnick[15] at 2.272 MeV. Since (d,α) particularly favors configurations such as $(f_{7/2})^{-2}_{J=7}$, the 7^+ assignment seems most probable. This level corresponds to the 7^+ of form $|2\rangle$ predicted at 2.86 MeV by the weak coupling model. This is particularly favorable for pickup reactions which are the only ones to report this state. Calculations with McGrory's wave functions yield a reasonable fit for 6^+ or 7^+. However, the strength calculated for the 7^+ (N = 40) is much more reasonable than for the 6^+_1 (N = 220). The corresponding wave functions 7^+_1 is mainly $[(f_{7/2})^{-2}_7(p_{3/2})^2_{0,2}]_{7^+}$ which is type $|2\rangle$ as expected.

We have observed no L = 2 transition near 2.3 MeV. Our resolution did not allow us to separate this state from the observed 2.271 MeV level, but if the (p, ^3He) experiment allows the excitation of an L = 2 level here, it is weakly excited. This suggests that the strong (L = 2) 2.296 MeV level observed in Ref. 10 can be the 3^+ state of configuration $|1\rangle$ predicted at 2.62 MeV by the weak coupling model. The 2.371 MeV state is weakly excited and yields a structureless angular distribution.

The well separated 2.456 MeV level displays an L = 0 angular distribution but can be compared with the calculated curves corresponding to either the 0^+_2

(T = 1) or 1_2^+ (T = 1) states with comparable normalizations (Fig. 2). No possible 1^+ state has been observed in the previous (^{3}He, p) experiments (Table I). This level could be compared with the predicted 3.78 MeV 1^+ state described by the component $|2\rangle$, but it is unexpectedly weakly excited and its excitation energy is rather low. On the other hand, this state should not be observed at all in the (^{3}He, p) experiment (Fig. 8) whereas the observation of an eventual 0^+ state is allowed. The observation of a single 2.460 MeV level in the Pittsburgh (d,α) experiment[15] is a good indication that this level is 1^+ and not 0^+, but this state corresponds probably to a more complicated structure.

Levels above 2.5 MeV

Above 2.5 MeV, the level density is increased, making more questionable any further identification with McGrory's predicted states, except for a few selected states.

The 2.626 MeV level displays an L = 2 angular distribution which suggests a 2^+ or 3^+ spin assignment, if the (d,α) experiment had not indicated that there is a doublet at 2.597 - 2.623 MeV.

The 2.736 MeV level displays a straight line angular distribution which might suggest a 1^+ assignment. But once more the most recent (d,α) experiment[15] report a doublet at a corresponding energy, just as for the 3.048 (4^+?), 3.137 (3^+?) and 3.396 (2^+, 3^+?) levels.

Analog States

The existence of an L = 0 doublet around a 3.55 MeV excitation energy has been observed by Belote *et al.*[9] This doublet has also been investigated by the (^{3}He,t) experiments.[17,18,19,20] Levels are reported at 3.587 and 3.585 MeV in (d,α) experiments[9,15] but they are weakly excited and can be other states. Dzubay *et al.*[20] have reported 8 states between 3.362 and 3.614 MeV (Table I).

They definitely assign the 3.522 and 3.592 MeV states spins $0^+(T = 1)$ and 0^+ $(T = 2)$ respectively, with a certain isospin impurity. We have measured $L = 0$ angular distributions for levels at 3.501 and 3.587 MeV.

If one refers to the weak-coupling model, dealing with pure configurations, the (p, ^{3}He) reaction is expected to select the term $\frac{0}{7}\big|\frac{2}{7}$ in components $|3\rangle$ and $|4\rangle$. Then the ratio of the expected cross sections for the analog $T = 2$ and antianalog $T = 1$ states is

$$R = \frac{d\sigma/d\Omega\ (T = 2)}{d\sigma/d\Omega\ (T = 1)} = 1 \quad .$$

Matching the experimental angular distributions for the 3.587 and 1.444 MeV states, we find $R = 1.6 \mp 0.4$, which is compatible with the previous determinations of 1.67[12] and 1.2[9] in (^{3}He, p). It is difficult to draw any significant conclusion from this ratio with respect to the pairing vibration model since, in our experiment, the cross section ratio can be modified by the presence of additional unresolved states close to the 3.587 MeV level. In addition, however, a small amount of 4 particle-2 hole components in the ^{58}Ni ground state can drastically affect the experimental value for this ratio.

The ratio of the cross sections for the 3.587 and 3.501 MeV levels has been found to be 1.4 ∓ 0.5 in the present experiment. In the same way this ratio has to be compared with the value of 2 found by Dzubay[20] in (^{3}He, t), and the value of 2 drawn from the Belote (^{3}He, p) experiment.[9] McGrory's wave functions do not take into account the isospin mixing observed for these states by Dzubay et al.[20] They lead to calculated angular distributions which are both too weak, but the large normalization we get for the 3.501 state suggests this level is not the 0_2^+, $T = 1$ of McGrory. The calculated cross section for the previously known analog 2^+, $T = 2$ state is slightly small.

Additional States

The 5.090 and 5.187 MeV levels are strongly excited, especially the first one. The angular distribution for the 5.187 MeV level can be classified as L = 2, but that corresponding to the 5.090 MeV does not display any significant pattern. Considering that the most strongly excited state in the low energy spectrum corresponds to an $(f_{7/2}^{-2}, p_{3/2}^{2})_{7^+}$ configuration, the strength of the 5.090 MeV level suggests that it might result from the pickup of a deeper $d_{3/2}$ nucleon pair, leading to the 3^+ state in the $(d_{3/2}^{-2}, p_{3/2}^{2})$ configuration.

Simple considerations allow an estimate for the excitation energy of this 3^+ state. It is possible to evaluate the spacing ΔE between the $(f_{7/2}^{-2}, p_{3/2}^{2})_{7^+}$ state at 2.271 MeV and the $(d_{3/2}^{-2}, p_{3/2}^{2})_{3^+}$ state

$$\Delta E = \varepsilon_p + \varepsilon_n + M_1 - M_2 \quad ,$$

where ε_p and ε_n are the proton and neutron single particle energy differences between the $1f_{7/2}$ and $1d_{3/2}$ shells, respectively, and which can be taken from Ref. 46, and are $\varepsilon_p = \varepsilon_n = 2.1$ MeV and M_1 and M_2 are the residual interaction matrix elements between, respectively, two $f_{7/2}$ holes coupled to 7^+, T = 0 and two $d_{3/2}$ holes coupled to 3^+, T = 0. M_1 can be calculated in ^{38}K using the code PHYLLIS[47] with True's[48] potential and is found to be 2.4 MeV. M_2 is already known to be 2.6 MeV.[16] Thus the 3^+ state is expected to be about 6.3 MeV excitation and the 1^+ at 7 MeV. These are not too far from the measured energies. Assuming then that both levels have T = 1 and a simple shell model wave function for the ^{58}Ni ground state, we have calculated angular distributions for spins 0^+, 1^+, 2^+, and 3^+.

Figure 2 shows that the calculated angular distribution for the 3^+ state does not agree very well with the experimental results for the 5.090 MeV state. A better agreement is obtained if the curve calculated for the 1^+ state of the same configuration is added, (dashed curve). That could indicate that either this level is not resolved from another L = 2 state, or that there are in the wave function configuration mixtures which provide a strong L = 2 component.

In contrast, the 5.187 MeV angular distribution is well reproduced by any L = 2 calculation ($J^\pi = 2^+$ or 1^+). The renormalizations for these calculations are given with the figures and do not allow any further identification. If the 5.090 MeV state is a 3^+ with the proposed structure, then it should be observed in the ^{58}Ni (d,α) experiment. Hjorth[14] observed a strong level at 5.18 MeV excitation energy which could be one of these states. Furthermore, such a level must be observed in other (p, ^{3}He) or (d,α) experiments, on the iron isotopes for example. The excitation energy of these states can be predicted either from the ground state of the target nucleus or from the first strong 7^+ if it is known. In ^{52}Mn for instance, the 7^+ state is known[49] at 0.85 MeV and one would expect such a state about 2.75 MeV above the 7^+ (as in ^{56}Co), which is an excitation energy of about 3.6 MeV.

B. ^{56}Ni

The states observed in the present experiment include all but one of those reported by Davies *et al.*[24] In addition, the better energy resolution of the present experiment permitted detection of ten new levels as indicated in Table II. Many of the excitation energies reported here appear to be inconsistent with those reported in Ref. 24. However, they agree very well with the result of Miller and Kavanagh,[11] and are consistent with our energy determination for ^{56}Co.

L-value assignments agree with Ref. 24 with one exception. The 5.339 MeV state has been reported to be 2^+, while the present work measures an angular distribution which is flatter than a 2^+, suggesting perhaps a 6^+.

Of the other five states for which spin assignments have been made, two (6.222, 6.554) must be considered only tentative, inasmuch as agreements with experimental data are rather poor. The assignments of 3^- to the state at 5.483 MeV, 2^+ to the 6.318 MeV state, and 0^+ to the 7.289 MeV state, appear more certain.

The possible energy levels of ^{56}Ni may be constructed by considering ^{58}Ni to consist of a closed shell plus two paired valence neutrons in the $p_{3/2}$, $f_{5/2}$ or $p_{1/2}$ shells. A (p,t) experiment would then be expected to excite states of the form $(f_{7/2})^{16}_{J=0}$ by pickup of the two valence neutrons;
$[(f_{7/2})^{15}(p_{3/2})]_{J=2^+,4^+}$; $[(f_{7/2})^{15}(f_{5/2})]_{J=2^+,4^+,6^+}$; and $[(f_{7/2})^{15}(p_{1/2})]_{J=4^+}$
by the pickup of one core and one valence neutron. In addition, a large number of two particle-two hole states may be constructed which result from pickup of two core-nucleons.

The 2 particle-2 hole states may be discussed in terms of weak-coupling as was done for ^{56}Co. However, its complete construction should require a knowledge of the levels of ^{54}Ni and ^{58}Zn which are not available, and in addition the level scheme which can be deduced from the known ^{54}Co and ^{58}Cu states is much more complicated than for ^{56}Co. Discussion will, therefore, be limited to some 0^+ states. The reference level is assumed to be the first observed 0^+ at 5.000 MeV. Other T = 0 states are then predicted at 7.91, 8.08, 9.4 and 10.14 MeV. Only the 5.000 MeV state has a configuration which allows it to be observed through the ^{58}Ni(p,t) reaction unless there is some level mixing.

Perhaps the most serious flaw in this picture is that it ignores the presence of more complicated configurations in the ^{56}Ni ground state. Wong and Davies[2] have shown that some 2 particle-2 hole and 4 particle-4 hole configurations are necessary in order to obtain any agreement with the experimentally observed energy levels. Unfortunately the inclusion of 4 particle-4 hole configurations would make a calculation such as McGrory's completely impractical.

As a result, McGrory's calculations yield an energy spectrum in which the ground state-2_1^+ spacing is much too large. This is just the effect observed by Wong and Davies. In addition, since the configuration space is limited to the $1f_{7/2}$, $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$ shells, negative parity states cannot be described. Experimentally, at least three negative parity states are observed, presumably resulting from pickup from the $d_{3/2}$ shell.

In spite of this, however, the positive parity states have been compared with McGrory's calculations, as shown in Fig. 6 and listed in Table V. The first five excited T = 0, J ≠ 0 states are described as mainly $[(f_{7/2}{}^{15})_{7/2}(\ell_j)_j]_J$. Examination of the normalizations obtained using this description indicates that it is fairly reasonable. In addition this accounts for all but one (4_3^+) of the states which one can form by means of simple one-particle-one hole configurations.

At higher excitation energies one expects to see the more complicated 2 particle-2 hole states. Comparison of states at E = 6.318 MeV and E = 6.554 MeV with McGrory's wave functions yields the normalizations shown in Table V. The value N = 64 is quite reasonable and compares very well with those obtained for one-particle, one-hole states. The normalization for the 2_4^+ (N = 375) is quite large; however, the fit is rather poor and perhaps the level is not really a 2^+.

Also observed in the present experiment were four 0^+, T = 0 states (E = 0., 5.000, 6.644 and, perhaps, 7.289 MeV). Again this is just the number which one would expect to result from the configurations $(f_{7/2}^{16})_{J=0}$, $(f_{7/2}^{-2}\, p_{3/2}^{2})_{J=0}$, $(f_{7/2}^{-2},\, f_{5/2}^{2})_{J=0}$ and $(f_{7/2}^{-2}\, p_{1/2}^{2})_{J=0}$. In terms of weak coupling,3 excited 0^+ states are expected at 5.000, 7.91, and 10.14 MeV. This is somewhat different from the experimental values. Except for the first, however, which is the ground state, the calculated wave functions for the 0^+ states exhibit considerable configuration mixing. Nevertheless, the normalizations for all but the 0_3^+ state (E = 6.644 MeV) are quite reasonable, in comparison with the one particle-one hole states. The large normalization constant (N = 8500) for 6.644 MeV level suggests that this level is not the 0_3^+ level predicted by McGrory. If this level is compared to the following 0_4^+ state a much more reasonable N value (N = 120) is obtained. The apparent failure of the weak coupling model can be due to either a strong mixture of these 0^+ states or to a poor choice for the reference 0^+ state.

Wong and Davies[2] showed previously that a strong four-particle, four-hole component is needed to account for the observed energies of the low lying states in ^{56}Ni. Pure two particle two hole components give higher excitation energies. The 5.000 MeV 0^+ level may not be the suitable reference for the (T = 0) 2 particle-2 hole states. This energy can be estimated if one considers that the 0^+ states deduced from the coupling of the 0^+ T = 1 levels in ^{58}Cu and ^{54}Co may have isospin T = 0, 1 or 2. The energy separations between these states can be evaluated through a simplified relation deduced from Zamick's formalism[42]

$$E = E_0 + \frac{b}{2}\, T\,(T + 1) \quad ,$$

where E_0 depends upon the ^{56}Ni structure and b has been defined earlier. We have established in ^{56}Co that b = 1.07 MeV. We shall see that the 0_1^+ T = 1 state lies at 7.912 MeV in ^{56}Ni. This allows us to expect the corresponding T = 0 and T = 2 states at 6.84 and 10.05 MeV excitation energies respectively. The 6.644 MeV level is a reasonable candidate to be the former state. In addition, in the same way as we did for the (T = 1) and (T = 2) 0^+ states in ^{56}Co, it is possible to predict relative strengths for these T = 0, 1 and 2 states. In the (p,t) reaction, they are expected to be proportional to 1/3, 1/2 and 1/6 respectively. The experimental value of the ratio

$$R_\sigma = \frac{\sigma(E = 7.912 \text{ MeV})\ T = 1}{\sigma(E = 6.644 \text{ MeV})\ T = 0} = 1.5 \pm 0.3 \quad ,$$

is a further indication that the 6.644 MeV state is the right reference state for the 2-particle, 2-hole levels predicted by the weak coupling model in ^{56}Ni.

The wave function predicted by McGrory for the 0_4^+ state has effectively the suitable structure. The 7.289 MeV level has been tentatively assigned 0^+ and could be another candidate. However, the corresponding R_σ value, smaller by a factor of two, is less convincing. The predicted energy value for the (T = 2) 0^+ state is in good agreement with the previous experimental determination: 9.90 ∓ 0.10 MeV.[50] Three negative parity states have been observed here. Drawn in Fig. 4 are calculated curves which correspond to simple shell model wave functions for these states, assuming the pick-up of an s-d shell neutron. The 3^- assignment for the 7.567 MeV state is consistent with that of Davies et al.[24] The 5.483 MeV level is a good candidate to be the first 3^- state as suggested by the figure where the previous energies measured by (α,α') inelastic scattering for the first 2^+ and higher 3^- states in the Z = 28 and N = 28 nuclei are displayed.[51,52]

C. Isobaric Analog States

A number of pairs of states have been seen in the (p,t) and (p, ^{3}He) reactions which appear likely to be isobaric analogs. Figure 10 compares all the states observed in the two reactions. In this figure the ^{56}Co ground state is aligned with the 6.419 MeV 4^+, whose energy is very close to the value (6.40 MeV) estimated from Ref. 53 and using the ^{56}Co(p,n) Q value calculated by Mattauch et al.[54] It appears likely then that only two excited state analogs have been observed, namely the 2^+ at 1.001 MeV and the 0^+ at 1.444 MeV in ^{56}Co. Selection rules for (p,t) of course forbid the excitation of unnatural parity states, or if they are excited they may not have shapes characteristic of any angular momentum, or the appropriate strengths.

If the states in question are isobaric analog pairs, then one should be able to estimate the ratio of the (p,t) to (p, ^{3}He) cross sections (R). This is given by Hardy et al.[55] when both nucleons are picked up from the same shell, as

$$R_0 = (k_t/k_{^3He})(2/T_f) \quad ,$$

where T_f, is the isospin of the final level. Here, T_f equals 1. Otherwise

$$R_1 = R_0[1 + \frac{1}{3}\frac{\lambda^2}{T^2}\ \frac{(T_f + 1)^2}{L(L + 1)}]^{-1} \quad ,$$

where

$$\lambda = [\ell_1(\ell_1 + 1) - \ell_2(\ell_2 + 1)] - [j_1(j_1 + 1) - j_2(j_2 + 1)]$$

$$T = [t_1(t_1 + 1) - t_2(t_2 + 1)] - [t_1'(t_1' + 1) - t_2'(t_2' + 1)] \quad ,$$

if the nucleons are removed from shells $n_1\ell_1 j_1$ and $n_2\ell_2 j_2$ which have isospin t_1, t_2 respectively before the transition, t_1' and t_2' after the transition.

The values for this ratio, both experimental and calculated are given in Table VI. It is clear that both the 4^+ and 0^+ have just the expected strength. The 0^+ can only be formed by removal of two $f_{7/2}$ nucleons, so that R must have the value 1.7. Similarly, if the ground state of ^{56}Co is $[(f_{7/2})^{-1}(p_{3/2})]_4$ then it is formed mainly through pickup of an $f_{7/2}$ - $p_{3/2}$ nucleon pair and R should be 1.59, which is consistent with the observed value. For the 2^+, however, R experimental is considerably larger than the predicted upper limit (R_0) even after taking account of the larger error which results from the fact that the ^{56}Co peak is one of a poorly resolved doublet. This large value for R might result from the presence of an unresolved state in the ^{56}Ni, or it might indicate that the 2^+ state in nickel is not really the analog of the cobalt level. A better resolution experiment would help to resolve this question.

CONCLUSION

Both the (p, ^{3}He) and (p,t) reactions have been studied on the ^{58}Ni target nucleus. Some of the observed levels have been discussed in terms of a weak coupling model. As far as possible the experimental results have been compared with microscopic shell model calculations showing a reasonable overall agreement. There is experimental evidence, at least in ^{56}Co, that above 2.5 MeV excitation energy the experimental resolution has limited the possibilities for interpretation. In the (p, ^{3}He) experiment, two levels are preferentially excited which can be described in terms of pickup of a nucleon pair coupled to maximum J. Most of the other observed levels have comparable strengths. This does not favor the comparison to either a weak coupling model or McGrory's calculations.

Our experimental results seem to indicate that any model which can predict energies more accurately will be helpful because of the possible ambiguities due to the similarities of experimental angular distributions.

The present experiment provides best angular momentum matching at $L = 2.4\ \hbar = [(\vec{k}_i - \vec{k}_f)R]$ and therefore forms L = 2 components preferentially. It would be valuable to compare the results of this experiment, not only to other types of experiment, but also to other (p, ^{3}He) investigations at higher energy. For example, using a 70 MeV proton beam one might expect changes in angular distributions corresponding to mixed L transitons, since the higher energy would favor the higher (L = 4) value.

In the (p,t) reaction, the selection rules remove these ambiguities and allow unique spin assignments once an L value is determined. Consequently, in the present experiment, six new spin assignments have been suggested. In comparing experimental results with McGrory's calculations, it is clear that his wave functions give very poor predictions for excitation energies. On the other hand, employing the criteria which we have adopted for comparing theoretical and experimental results, one can obtain reasonably good estimates for the cross sections, especially the 1 particle-1 hole states.

Finally, the relative strengths of states excited via (p, ^{3}He) and (p,t) reactions provides additional evidence for the assignment T = 1 to the 6.419, and 7.912 MeV levels in ^{56}Ni. However, a further experiment is required for the 7.456 MeV 2^+.

ACKNOWLEDGMENTS

Both of us want to thank Dr. B. G. Harvey for the warm hospitality of his laboratory. It is also a pleasure to thank Prof. R. Sherr for many illuminating discussions of ^{56}Co and ^{56}Ni, Dr. J. B. McGrory for his interest in these experiments and the calculation of wave functions and spectroscopic amplitudes for ^{56}Ni and ^{56}Co, Dr. J. C. Hardy who introduced us to double particle transfer and provided his computing code, Mr. M. S. Zisman, Mr. J. D. Sherman and Miss J. Mahoney for their help before and during the experiments, and Mr. C. Ellsworth, who made the ^{58}Ni target.

FOOTNOTES AND REFERENCES

*Work performed under the auspices of the U. S. Atomic Energy Commission.

†NATO Fellow on leave from CEN de Saclay, France. Permanent address: DPhN/ME Centre d'Etudes Nucleaires de Saclay, France.

††Permanent address: NASA Lewis Research Center, Cleveland, Ohio.

1. J. Vervier, Nucl. Phys. 78, 497 (1966).
2. S. S. A. Wong and W. G. Davies, Phys. Letters 28B, 77 (1968).
3. J. B. McGrory, private communication.
4. D. O. Wells, S. L. Blatt and W. E. Meyerhof, Phys. Rev. 130, 1961 (1963).
5. R. C. Jenkins and W. E. Meyerhof, Nucl. Phys. 58, 417 (1964).
6. C. J. Piluso, D. O. Wells and D. K. McDaniels, Nucl. Phys. 77, 193 (1966).
7. M. Onhuma, Y. Hashimoto and I. Tomita, Nucl. Phys. 66, 337 (1965).
8. C. M. Lederer, J. M. Hollander and I. Perlman, Table of Isotopes, sixth Ed., John Wiley and Sons Inc., New York.
9. T. A. Belote, W. E. Dorenbusch and J. Rapaport, Nucl. Phys. A109, 666 (1968).
10. J. M. Laget and J. Gastebois, Nucl. Phys. A122, 431 (1968).
11. R. G. Miller and R. W. Kavanagh, Nucl. Phys. A94, 261 (1967).
12. C. Shin, B. Povh, K. Schadewalt and J. P. Wurm, Phys. Rev. Letters 22, 1124 (1969).
13. J. M. Bjeregaard, P. F. Dahl, O. Hansen and G. Sidenius, Nucl. Phys. 51, 641 (1964).
14. S. A. Hjorth, Ark. Fys. 33, 147 (1966).
15. M. Schneider and W. W. Daehnick, Bull. Am. Phys. Soc., January 1970, Ed. 4, p. 62 and W. W. Daehnick, private communication.
16. C. C. Lu, M. S. Zisman and B. G. Harvey, Phys. Rev. 186, 1086 (1969).
17. F. D. Bechetti, Jr., D. Dehnard and T. G. Dzubay, proceedings of the second conference on the nuclear isospin, Asilomar, Academic Press, New York, 1969, p. 171.

18. P. G. Roos and C. D. Goodman, ibid p. 297.

19. G. Bruge, A. Chaumeaux, Ha Duc Long, P. Roussel and L. Valentin, Bull. Am. Phys. Soc., December 1969, AE7 p. 1208.

20. T. G. Dzubay, R. Sherr, F. D. Bechetti, and D. Dehnard, Nucl. Phys. A142, 488 (1970).

21. C. Maples, G. W. Goth and J. Cerny, Nucl. Data Vol. 2, (1966), p. 429.

22. G. Bassani, N. M. Hintz, and G. D. Kavaloski, Phys. Rev. 136, B1006 (1964).

23. C. G. Hoot, M. Kondo and M. Rickey, Nucl. Phys. 71, 449 (1965).

24. W. G. Davies, J. E. Kitching, W. McClatchie, D. G. Montague, K. Ramavataram, and N. S. Chant, Phys. Letters 27B, 363 (1968).

25. N. K. Glendenning Phys. Rev. 137, B102 (1965).

26. I. S. Towner and J. C. Hardy, Advances in Physics 18, 401 (1969).

27. J. C. Hardy and I. S. Towner, Phys. Letters B25, 98 (1967).

28. V. Gillet and N. Vinh-Mau, Nucl. Phys. 54, 321 (1964).

29. N. K. Glendenning, Tables of Structure Amplitudes for the (p, ^{3}He) Reaction, Lawrence Radiation Laboratory Report UCRL-18269, unpublished.

30. N. K. Glendenning, Tables of Structure Amplitude for the (p,t) Reaction, Lawrence Radiation Laboratory Report UCRL-18268, unpublished.

31. Code written by P. D. Kuntz, unpublished.

32. M. H. Fricke, E. E. Gross, B. J. Morton, and A. Zucker, Phys. Rev. 156, 1207 (1967).

33. M. P. Fricke and G. R. Satchler, Phys. Rev. 139, B567 (1965).

34. P. E. Hodgson, Advance in Phys. 17, 563, and included references.

35. E. R. Flynn, D. D. Armstrong, J. G. Berry, and A. G. Blair, Phys. Rev. 182, 1113 (1969).

36. G. Gatroussis, R. A. Mayer, L. G. Mann, and J. B. McGrory, Phys. Rev. 180, 1052 (1969).

37. T. T. S. Kuo and G. E. Brown, Nucl. Phys. A114, 241 (1968).

38. A. Arima, M. Horiuchi, T. Sebe, Phys. Letters 24B, 129 (1967).

39. R. Sherr, T. S. Bathia, D. Cline and J. J. Schwartz, to be published.

40. H. Rudolf, R. L. McGrath, and P. J. Cooney, Bull. Am. Phys. Soc., April 1970, HF12, p. 479.

41. J. M. Moss, Ph.D. Thesis, Lawrence Radiation Laboratory Report UCRL-18902, April 1969.

42. L. Zamick, Phys. Letters 19, 580 (1965).

43. J. J. Schwartz, R. Sherr, and T. Bhathia, Bull. Am. Phys. Soc. 13, 1446 (1968).

44. O. Nathan, in International Symposium on Nuclear Structure, Dubna 1968. International Atomic Energy Agency, Vienna, Austria, 1969, p. 191.

45. R. Hinrichs, G. Crawley, and R. Sherr, to be published.

46. V. Gillet, B. Giraud, and M. Rho, Nucl. Phys. A103, 257 (1967).

47. M. S. Zisman, private communication.

48. W. W. True, Phys. Rev. 130, 1530 (1963).

49. G. Bruge, A. Bussiere, H. Faraggi, P. Kossanyi-Demay, J. M. Loiseaux, P. Roussel and L. Valentin, Nucl. Phys. A129, 417 (1969).

50. J. Cerny, Ann. Rev. Nucl. Sci. 18, 27 (1968).

51. R. J. Peterson, Phys. Rev. 140, B1479 (1965).

52. G. Bruge, J. C. Faivre, H. Farragi and A. Bussiere, Nucl. Phys. A146, 597 (1970).

53. R. Sherr, Phys. Letters 24B, 321 (1967).

54. J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. 67, 37 (1965).

55. J. C. Hardy, M. Brunnader, and J. Cerny, Phys. Rev. Letters 22, 1439 (1969).

TABLE CAPTIONS

Table I. Experimental determinations of the ^{56}Co levels.

a. This work

b. Ref. 8

c. Ref. 9

d. Ref. 10

e. Ref. 11

f. Ref. 13

g. Ref. 14

h. Ref. 15

i. Ref. 19

j. Ref. 20

k. Ref. 16

Table II. Summary of results of ^{58}Ni(p,t)^{56}Ni experiments.

Table III. Optical potentials used in the DWBA calculations.

Table IV. Numerical results for the ^{58}Ni(p, ^{3}He)^{56}Co experiment. Given for each level are the energy (MeV), strongest transferred angular momentum (L), cross sections integrated between 14 and 62° CM, the possible spin and parity referred to McGrory's predictions and the corresponding normalization constant N, as defined in the text.

Table V. Comparison of experimental and theoretical levels in ^{56}Ni. Odd spin states and states of undetermined spin have been omitted.

Table VI. See the table itself.

Table I.

this work		decay		$^{54}Fe(^{3}He, p)^{56}Co$					$^{58}Ni(d,\alpha)^{56}Co$							$^{56}Fe(^{3}He, t)^{56}Co$				$^{54}Fe(\alpha,d)$
a		b		c		d		e	f	g		c	d	h		i		j		k
E^*	J^π	E^*	J^π	E^*	L	E^*	L	E^*	E^*	E^*	L	E^*	E^*	E^*	J^π	E^*	J^π	E^*	J^π	E^*
0.	4^+	0.0	4^+	0.0		0.0	4	0.0	0.	0.	4	0.	0.	0.	4	0.0	4			
0.166	3^+	0.1583	3^+	0.155		0.167	2	0.166	0.158	0.167	2	0.160	0.165	0.157	2	0.160	3			
0.578	5^+			0.592		0.575	4	0.576	0.578	0.582	4	0.575	0.578	0.572	2+4	0.590	5			0.570
0.840	$4^+,5^+$							0.832	0.829	(0.810)	(4,2)	0.830	0.827	(0.824)	4					
0.961	3^+	0.9705	2^+	0.976		1.000	2	0.978	0.965			0.972		0.964	2					
1.001	2^+								1.008			1.008	1.013	1.003	2	1.000	2			1.010
										1.026	4									
1.106	$4^+,5^+$							1.111	1.111	(1.16)	2	1.116	1.121	1.107	2+4					
								1.246												
1.444	0^+	1.4512	$(1^-,2\pm)$	1.453	0	1.453	0	1.445	1.445			1.448				1.470				
								1.592						(1.670)						
1.714	1^+	1.7209	(1^+)	1.721	0+2	1.721	0+2	1.723	1.714	1.730	(0)	1.718	1.720	1.711	0	1.720				1.720
1.924	3^+			1.929	2	1.927	2	1.934	1.925	1.946	2	1.929	1.930	1.921	2	1.940				1.960
2.050	2^+			2.067		2.051	2	2.087	2.056	(2.040)	(2)	2.058	2.058	2.049	2	2.070				
2.220	2^+			2.244				2.225	2.222			2.224		(2.214)	2					
2.271	7^+			2.283		2.296	2	2.312	2.291	2.300	6	2.285	2.284	2.272	6	2.290				
														2.347						2.350
2.371								2.381	2.358			2.359		2.361						
2.456	1^+?					2.471	4			2.481	(0)	2.469	2.473	2.460						
												2.608		2.597						
2.626	$2^+,3^+$													2.623						
						2.647						2.636	2.635	(2.636)						
										2.650	4	2.667		(2.655)						
												2.725		2.717		2.720				
2.734	1^+?			2.744		2.740							2.750							
										2.780	(0)	2.773								
												2.927		(2.917)						
2.946				2.932		2.963	2					2.971		(2.960)		3.000				3.000
														(3.035)						
3.048	4^+?											3.048		(3.050)						
				3.069									3.061	3.061						
						3.081	2			3.080 }		3.077								
3.137	3^+?										2	3.129		3.129						3.130
						3.178	2			3.160 }		3.176		3.166		3.200				
												3.244		3.245						
												3.295		3.286		3.330				
3.396	$3^+,2^+$					3.385	2					3.373		3.373				3.362		
												3.431		3.422				3.423		
												3.505		(3.499)				3.489		
3.501	0^+			3.511	0									3.514		3.510	0	3.522	0^+	
														3.536				3.539		
3.587				3.577	0	3.613	0					3.587		3.585		3.590	0^+	3.592	0^+	3.570
																		3.602		
												3.703		3.699				3.694		
														3.781						
												3.796		3.794						
												3.846		3.849						
												3.873								
												3.934		3.992						
														4.014						4.010
						4.062	2							4.045						
														4.117						
										4.18	(4)			4.164		4.170				
4.432	2					4.451	2									4.450	2			
						4.993														4.980
5.090						5.097														
5.187	2									5.18										
						5.347														
																5.400				
																				5.440
						5.495														
																5.530				
																				6.560
																				8.920

Table II. Summary of Results of $^{58}Ni(p,t)$ Experiments

Excitation Energy, E, MeV		Spin and Parity, J^{π}		Integrated cross section σ, μb
Present Work	Ref. (24)	Present Work	Ref. (24)	Present Work
0.00	0.000	0^+	0^+	192.9 ± 19
2.697 ± 0.015	2.64	2^+	2^+	23.6 ± 2.8
3.956 ± 0.015	3.90	4^+	4^+	37.1 ± 4.1
5.000 ± 0.020	4.95	0^+	0^+	6.49 ± 1.50
5.339 ± 0.020	5.33	6^+	(2^+)	12.7 ± 1.7
5.483 ± 0.025		3^-		4.80 ± 1.12
5.989 ± 0.020	5.90	(4^+)	(4^+)	7.48 ± 1.37
6.222 ± 0.035		(2^+)		2.24 ± 0.74
6.318 ± 0.025		2^+		5.80 ± 1.25
6.419 ± 0.015	6.38	4^+	4^+	17.5 ± 1.93
6.554 ± 0.020		(2^+)		21.4 ± 2.55
6.644 ± 0.020	6.58	0^+	0^+	16.8 ± 2.12
7.021 ± 0.025	7.00	−		4.36 ± 1.0
7.170 ± 0.030	7.12	1^-	1^-	6.99 ± 1.37
7.289 ± 0.025		0^+		7.55 ± 1.50
7.455 ± 0.020	7.42	2^+	2^+	43.4 ± 4.3
7.567 ± 0.015	7.56	3^-	3^-	25.7 ± 2.55
7.653 ± 0.030		$(1^-,2^+)$		6.99 ± 1.37
7.788 ± 0.030				5.86 ± 1.75
7.912 ± 0.020	7.92	0^+	0^+	25.2 ± 2.7
(8.082) ± 0.100				
	8.48		2^+	
8.654 ± 0.020				
8.771 ± 0.025				
8.896 ± 0.020				

Table III.

Particle	Volume Real Part			Imaginary Part Volume			Imaginary Part Derivative			Spin Orbit Volume			Ref.	N°
	V (MeV)	r (fm)	a (fm)	W_I (MeV)	r_I (fm)	a_I (fm)	W_D (MeV)	r_D (fm)	a_D (fm)	V_{SO} (MeV)	r_{SO} (fm)	a_{SO} (fm)		
Proton	-49.49	1.109	0.782	-6.5	1.477	0.495	-2.08	1.477	0.495	5.53	1.071	0.641	32	1
	-45.05	1.16	0.75	-6.63	1.37	0.63	-1.22	1.37	0.63	6.04	1.064	0.738	33	2
	-42.7	1.211	0.707	-1.5	1.067	0.545	-10.3	1.067	0.545	7.67	1.211	0.707	36	3
He^3	-137.4	1.082	0.805	-16.1	1.66	0.795							36	4
	-172.6	1.147	0.712	-20.16	1.562	0.802							34	5
t	-154.3	1.24	0.677	-26.11	1.431	0.85							35	6
	-169.7	1.16	0.732	-22.8	1.510	0.796							35	7

Table IV. $^{58}Ni(p, He^3)^{56}Co$ Ep = 45 MeV

E(MeV)	L	σ(μb)	J^{π}_{n}	N	E(MeV)	L	σ(μb)	J^{π}_{n}	N
0.0	4	9.79 ± 1.68	4^+_1	18	2.371 ± 0.015	-	7.61 ± 2.3	-	-
0.166 ± 0.010	2	15.8 ± 1.90	3^+_1	60	2.456 ± 0.015	0	12.8 ± 2.2	1^+_2	366
0.578 ± 0.010	4	23.4 ± 2.80	5^+_1	25	2.626 ± 0.015	2	11.8 ± 2.	$2^+,3^+$	
0.84 ± 0.015	4	3.74 ± 1.25	$\begin{cases} 4^+_2 \\ 5^+_2 \end{cases}$	$\begin{cases} 170 \\ 8 \end{cases}$	2.734 ± 0.015	0+2?	9.54 ± 1.68	1^+?	
0.961 ± 0.015	2	10.9 ± 2.2	3^+_2	370	2.946 ± 0.020	-	2.2 ± 0.9		
1.001 ± 0.015	2	14.4 ± 2.9	2^+_1	35	3.048 ± 0.020	4	9.8 ± 1.7	4^+_3?	14
1.106 ± 0.015	4	4.06 ± 1.0	$\begin{cases} 4^+_2 \\ 5^+_2 \end{cases}$	$\begin{cases} 210 \\ 10 \end{cases}$	3.137 ± 0.015	2+4?	14.3 ± 2.3	3^+?	
1.444 ± 0.015	0	11.9 ± 1.8	0^+_1	98	3.396 ± 0.015	2	9.42 ± 1.9	$2^+,3^+$	
1.714 ± 0.015	0+2	5.67 ± 1.56	1^+_1	418	3.501 ± 0.015	0	15.7 ± 3.4	0^+_2	415
1.924 ± 0.015	2	15.2 ± 2.3	3^+_3	370	3.587 ± 0.015	0	19.5 ± 3.7	0^+_1 T=2	110
2.050 ± 0.015	2	22.6 ± 2.3	2^+_2	35	4.432 ± 0.020	2	15.8 ± 2.4	2^+_1 T=2	185
2.220 ± 0.015	2	4.49 ± 1.12	2^+_3	31	5.090 ± 0.020		51.4 ± 6.4		
2.271 ± 0.010	6	41.2 ± 4.1	7^+_1	40	5.187 ± 0.020	2?	15.4 ± 6.2	$1^+,2^+$?	

Table V.

J_n^π	$E_{experimental}$(MeV)	$E_{theoretical}$(MeV)	$N = \frac{\sigma(\text{experiment})}{\sigma(\text{theory})}$
		T = 0 States	
0_1^+	0.	0.	78
2_1^+	2.697	6.363	31
4_1^+	3.956	6.614	38
0_2^+	5.000	9.150	43
6_1^+	5.339	7.479	52
(4_2^+)	5.989	7.716	98
2_2^+	6.222	8.465	74
2_3^+	6.318	9.567	64
(2_4^+)	6.554	9.860	375
0_3^+	6.644	9.760	8500
0_4^+	7.289	11.168	48
		T = 1 States	
4_1^+	6.419	7.537	16
2_1^+	7.455	8.496	34
0_1^+	7.912	10.062	78

Table VI.[a]

Spins	$E(Co^{56})$	$E(Ni^{56} - 6.419)$	$R_{experiment}$	R_0	R_1	R_2
4^+	0. MeV	0. MeV	1.55 ∓ 0.3	1.7	1.59	0.94
2^+	0.960	1.036	4.5 ∓ 2.0	1.7	1.39	0.46
0^+	1.444	1.493	1.7 ∓ 0.3	1.7		

$$R = \sigma(p,t)/\sigma(p,\ ^3He)$$

[a]Energies and intensities of analog state pairs in ^{56}Ni and ^{56}Co. R_0 is the expected ratio $\sigma(p,t)/\sigma(p,\ ^3He)$ if both transferred nucleons are from the same shell; R_1 is for pickup from the $f_{7/2}$ and $p_{3/2}$ shells; R_2 is for pickup from the $f_{7/2}$ and $f_{5/2}$ shells.

FIGURE CAPTIONS

Fig. 1. Experimental spectrum for the $^{58}Ni(p, {}^{3}He)^{56}Co$ reaction.

Fig. 2. Angular distributions measured for the $^{58}Ni(p, {}^{3}He)^{56}Co$ reaction. The curves are calculated using McGrory's spectroscopic amplitudes when a spin is indicated. The others must be considered as DWBA curves. The curves relative to the 5.090 and 5.187 levels have been calculated assuming pure shell model wave functions for the ^{58}Ni gs and $[d_{3/2}^{-2}\ p_{3/2}^{2}]$ configurations for ^{56}Co. N is the normalization constant, as defined in the text.

Fig. 3. Experimental spectrum for the $^{58}Ni(p,t)^{56}Ni$ reaction.

Fig. 4. Angular distributions measured for the $^{58}Ni(p,t)^{56}Ni$ reactions. The curves correspond to DWBA predictions as explained in the text.

Fig. 5. Comparison of the ^{56}Co experimental spectrum to the theoretical predictions of Vervier and McGrory.

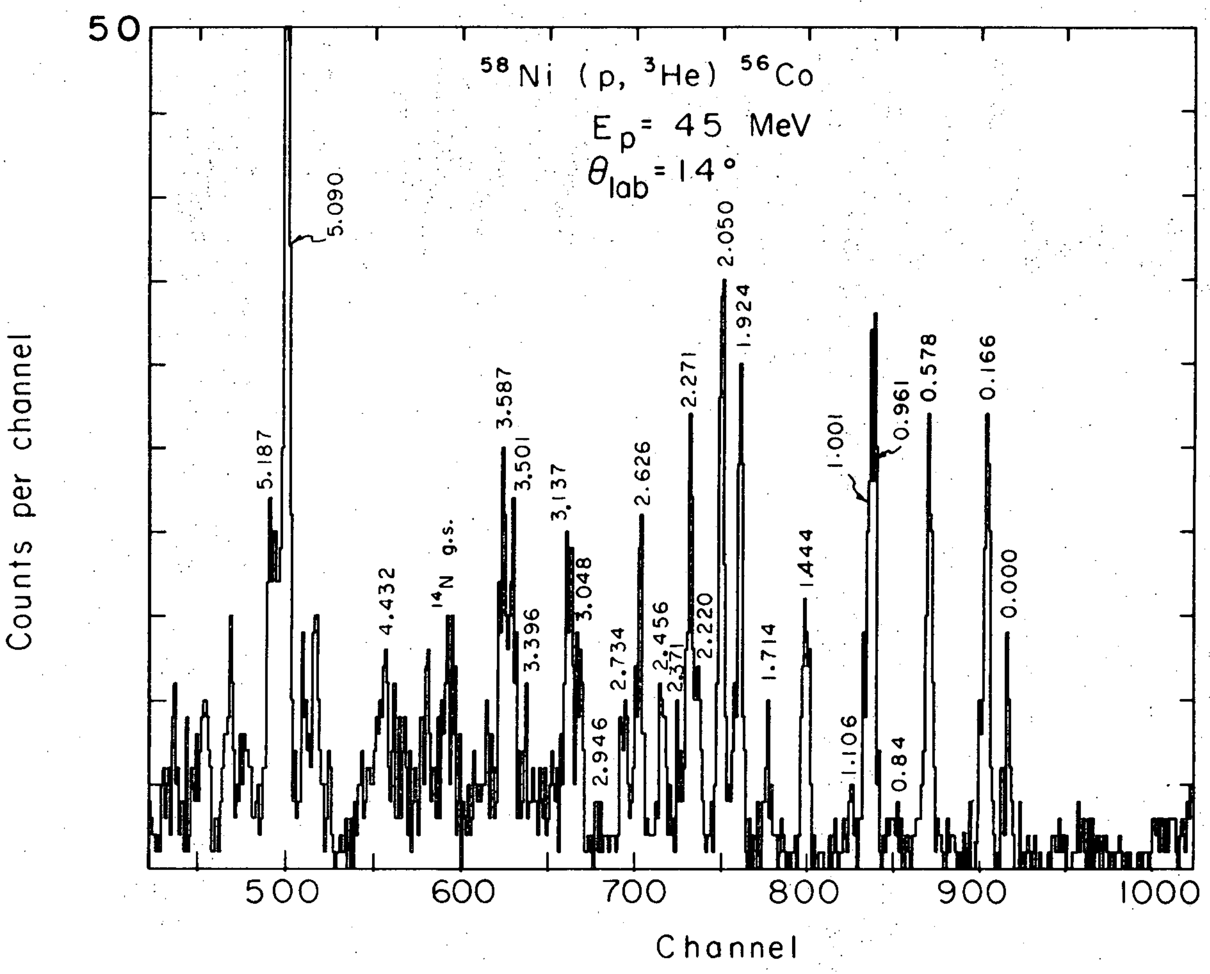
Fig. 6. Comparison of the ^{56}Ni experimental spectrum to the predictions of McGrory. Only the natural parity states are shown. For a more convenient presentation, the energies of the levels predicted by McGrory have been aligned on the first experimental 2^{+} state.

Fig. 7. Calculated angular distributions for the $^{58}Ni(p, {}^{3}He)^{56}Co$ reaction. The angular distributions corresponding to the first four 3^{+} states in McGrory's calculations, are compared to those for first four 2^{+} (L = 2) and first 4^{+} states.

Fig. 8. The integrated cross sections for the levels observed in the $^{58}Ni(p, {}^{3}He){}^{56}Co$ reaction (this work) are compared to a) those measured in the $^{54}Fe({}^{3}He, p){}^{56}Co$ experiment of Ref. 10 and b) to a ^{56}Co spectrum of the $^{56}Fe({}^{3}He, t)$ reaction.[19] The lines are proportional to the strengths.

Fig. 9. First 2^{+} and first and higher 3^{-} levels in the even N = 28 and Z = 28 nuclei.

Fig. 10. Comparison of the ^{56}Co energy levels to the states above 6.419 MeV in ^{56}Ni.



XBL701-2179

Fig. 1

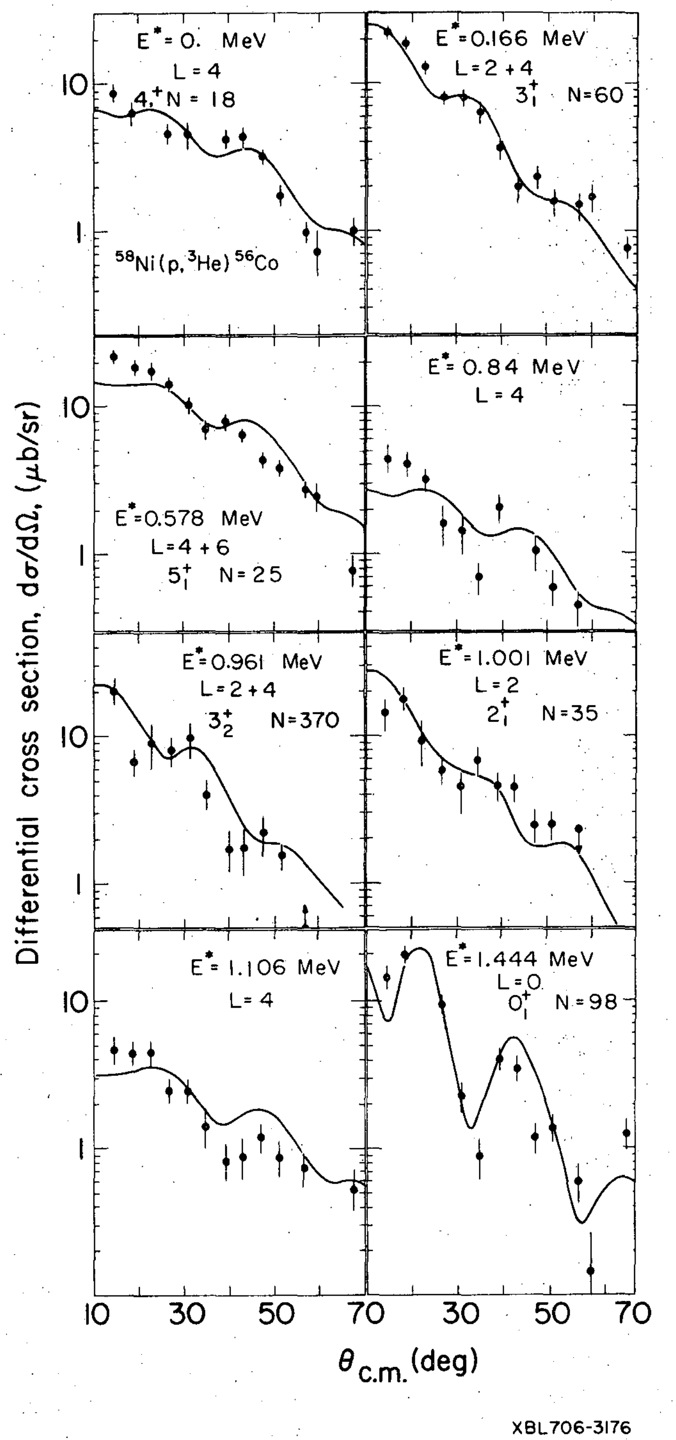

E* = 0. MeV
L = 4
4,+ N = 18
58Ni(p,3He)56Co
E* = 0.166 MeV
L = 2 + 4
3+1 N = 60
E* = 0.578 MeV
L = 4 + 6
5+1 N = 25
E* = 0.84 MeV
L = 4
E* = 0.961 MeV
L = 2 + 4
3+2 N = 370
E* = 1.001 MeV
L = 2
2+1 N = 35
E* = 1.106 MeV
L = 4
E* = 1.444 MeV
L = 0
0+1 N = 98
Differential cross section, dσ/dΩ, (μb/sr)
θc.m.(deg)
XBL706-3176

Fig. 2a

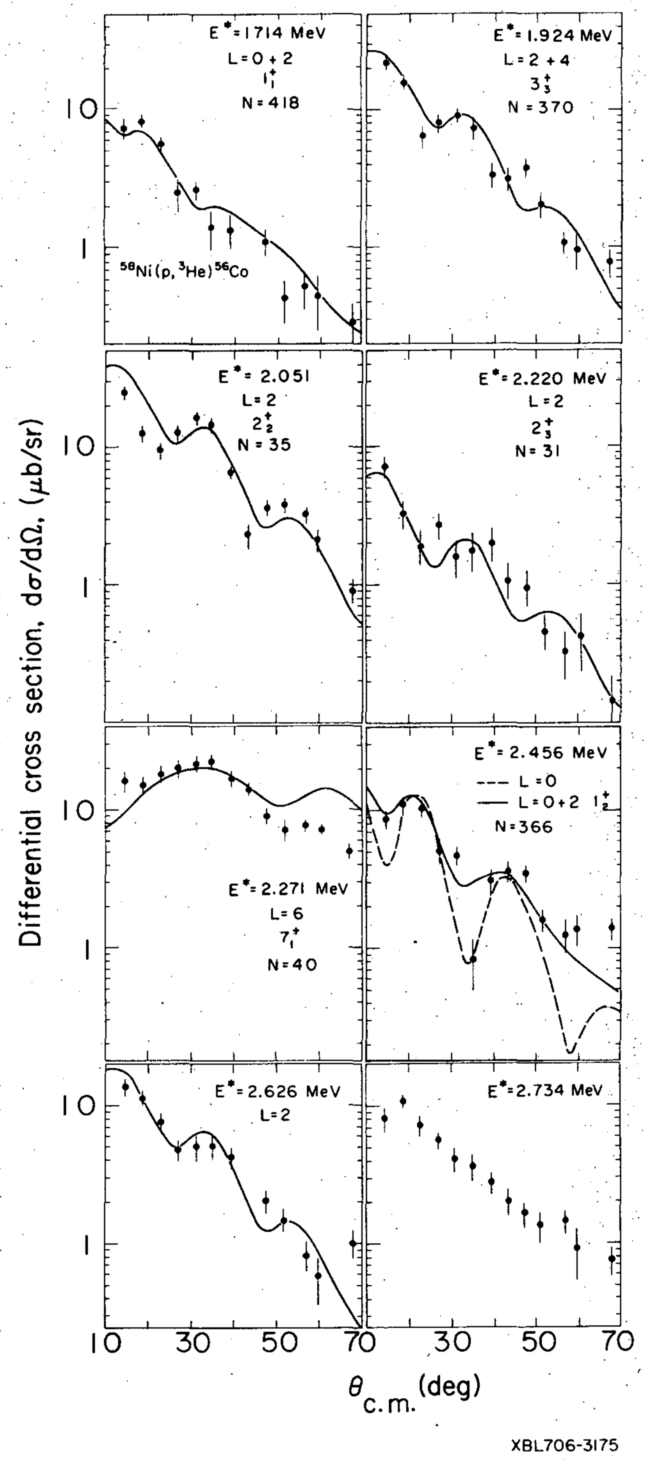

E* = 1.714 MeV
L = 0 + 2
1_1^+
N = 418
^{58}Ni(p, ^{3}He)^{56}Co
E* = 1.924 MeV
L = 2 + 4
3_3^+
N = 370
E* = 2.051
L = 2
2_2^+
N = 35
E* = 2.220 MeV
L = 2
2_3^+
N = 31
E* = 2.271 MeV
L = 6
7_1^+
N = 40
E* = 2.456 MeV
L = 0
L = 0+2 1_2^+
N = 366
E* = 2.626 MeV
L = 2
E* = 2.734 MeV
Differential cross section, dσ/dΩ, (μb/sr)
θ c.m. (deg)
XBL706-3175

Fig. 2b

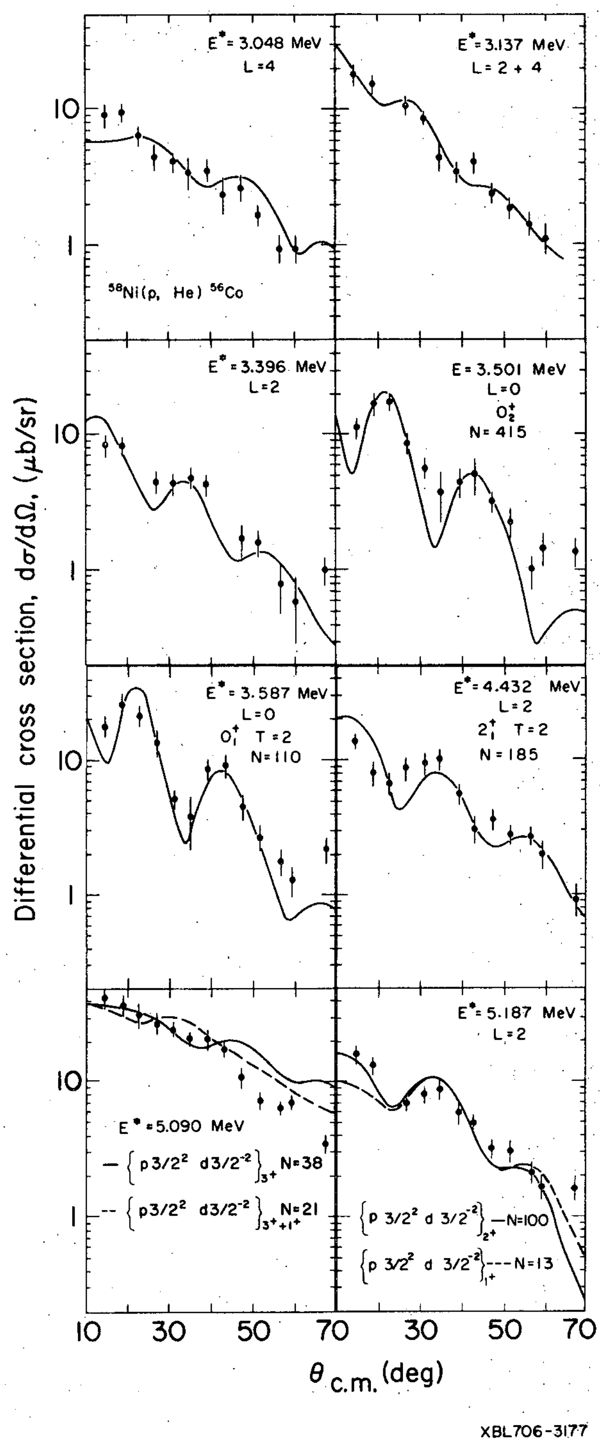
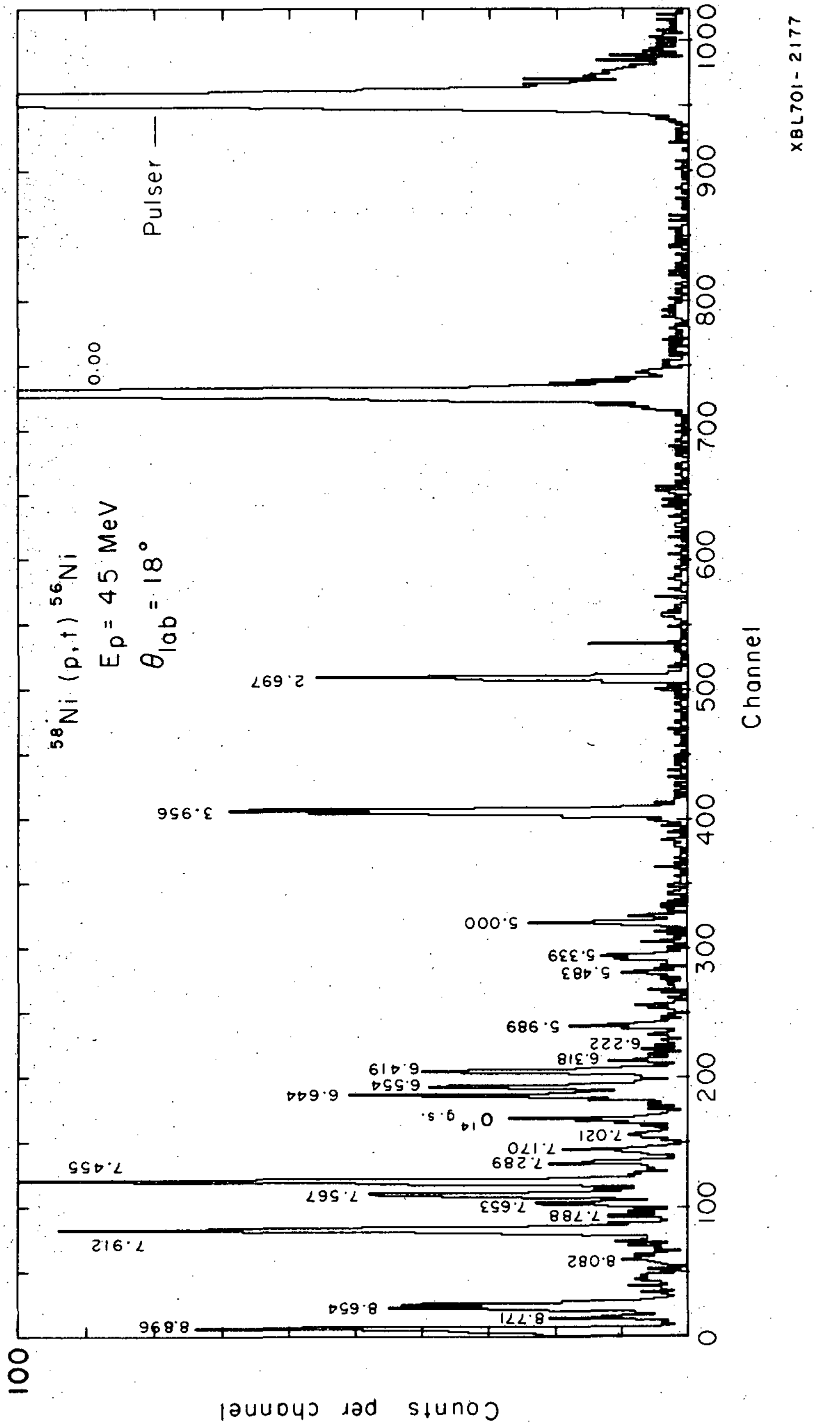

E* = 3.048 MeV
L = 4
58Ni(p, He) 56Co
E* = 3.137 MeV
L = 2 + 4
E* = 3.396 MeV
L = 2
E = 3.501 MeV
L = 0
0₂⁺
N = 415
E* = 3.587 MeV
L = 0
0₁⁺ T = 2
N = 110
E* = 4.432 MeV
L = 2
2₁⁺ T = 2
N = 185
E* = 5.090 MeV
{p3/2² d3/2⁻²}3+ N=38
{p3/2² d3/2⁻²}3++1+ N=21
E* = 5.187 MeV
L = 2
{p 3/2² d 3/2⁻²}2+ —N=100
{p 3/2² d 3/2⁻²}1+ ---N=13
Differential cross section, dσ/dΩ, (μb/sr)
θ c.m. (deg)
XBL706-3177

Fig. 2c



58Ni (p,t) 56Ni
Ep = 45 MeV
θlab = 18°
Pulser
0.00
2.697
3.956
5.000
5.339
5.483
5.989
6.222
6.318
6.419
6.554
6.644
O14 g.s.
7.021
7.170
7.289
7.455
7.567
7.653
7.788
7.912
8.082
8.654
8.771
8.896
Channel
Counts per channel
100
0
100
200
300
400
500
600
700
800
900
1000
XBL701-2177

Fig. 3

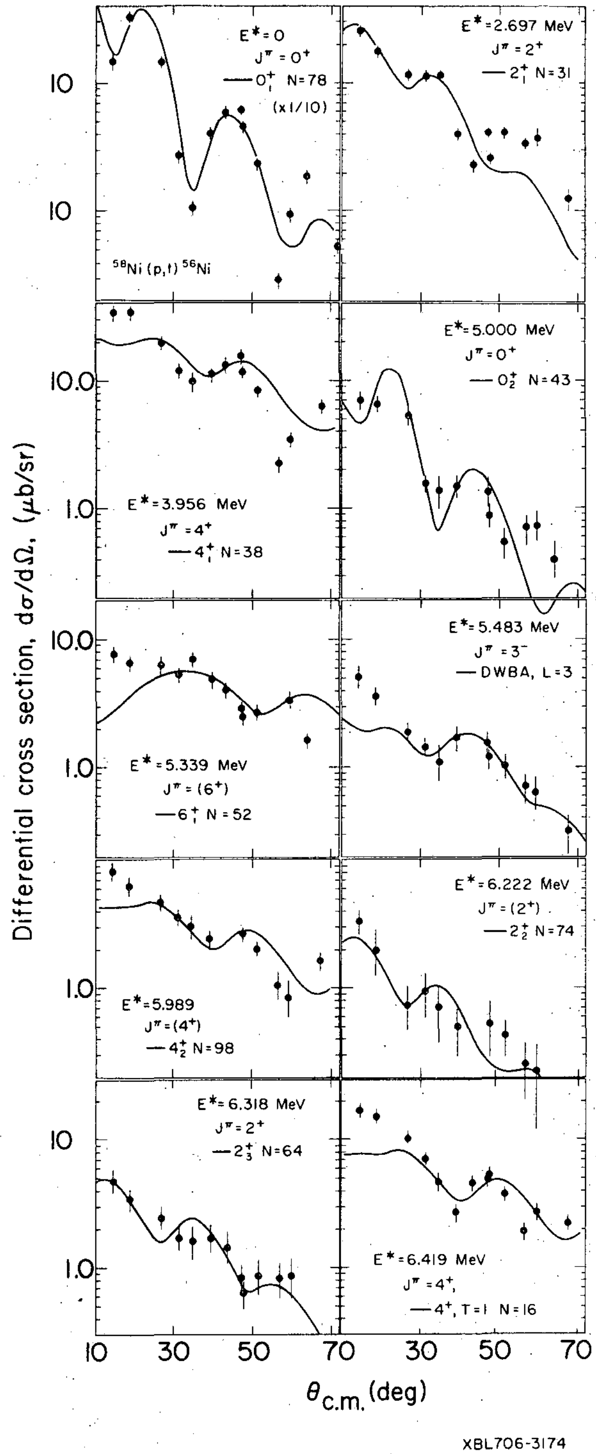

E* = 0
J^π = 0+
— 0+1 N=78
(x1/10)
58Ni (p,t) 56Ni
E* = 2.697 MeV
J^π = 2+
— 2+1 N=31
E* = 3.956 MeV
J^π = 4+
— 4+1 N=38
E* = 5.000 MeV
J^π = 0+
— 0+2 N=43
E* = 5.339 MeV
J^π = (6+)
— 6+1 N=52
E* = 5.483 MeV
J^π = 3−
— DWBA, L=3
E* = 5.989
J^π = (4+)
— 4+2 N=98
E* = 6.222 MeV
J^π = (2+)
— 2+2 N=74
E* = 6.318 MeV
J^π = 2+
— 2+3 N=64
E* = 6.419 MeV
J^π = 4+,
— 4+, T=1 N=16
Differential cross section, dσ/dΩ, (μb/sr)
θc.m.(deg)
XBL706-3174

Fig. 4a

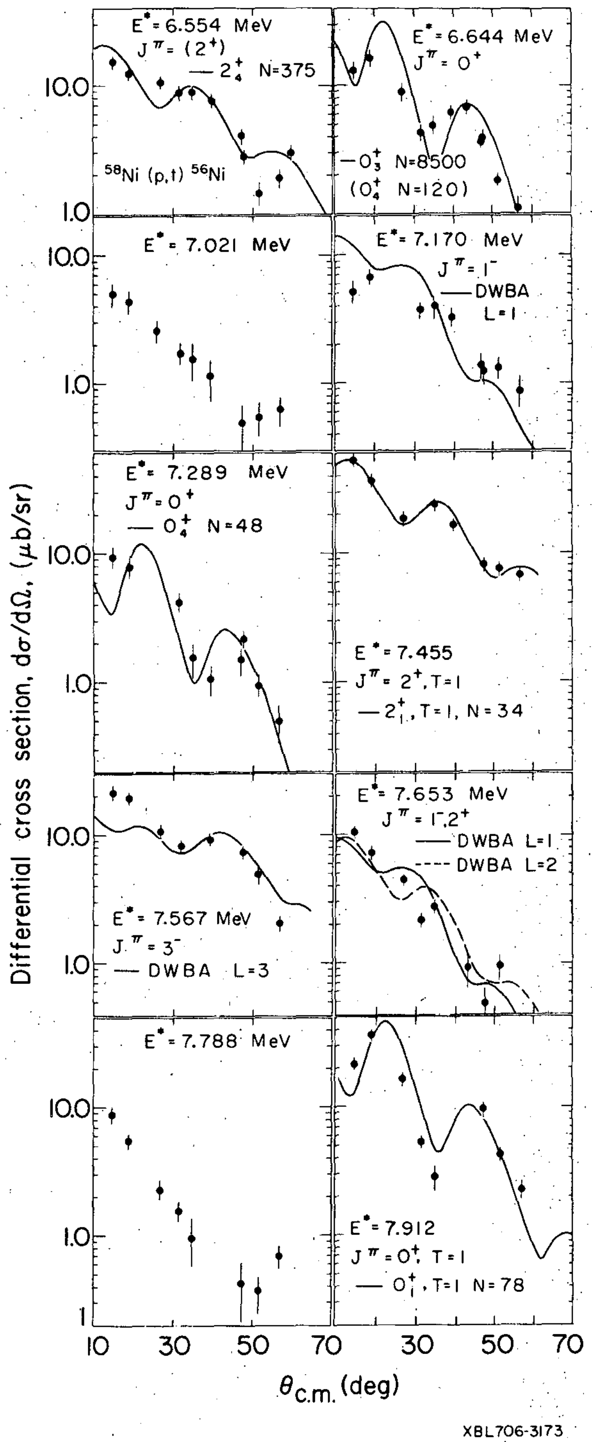

E* = 6.554 MeV
J^π = (2+)
— 2+4 N=375
58Ni (p,t) 56Ni
E* = 6.644 MeV
J^π = 0+
— 0+3 N=8500
(0+4 N=120)
E* = 7.021 MeV
E* = 7.170 MeV
J^π = 1-
— DWBA L=1
E* = 7.289 MeV
J^π = 0+
— 0+4 N=48
E* = 7.455
J^π = 2+, T=1
— 2+1, T=1, N=34
E* = 7.567 MeV
J^π = 3-
— DWBA L=3
E* = 7.653 MeV
J^π = 1-, 2+
— DWBA L=1
---- DWBA L=2
E* = 7.788 MeV
E* = 7.912
J^π = 0+, T=1
— 0+1, T=1 N=78
Differential cross section, dσ/dΩ, (μb/sr)
θc.m. (deg)
XBL706-3173

Fig. 4b

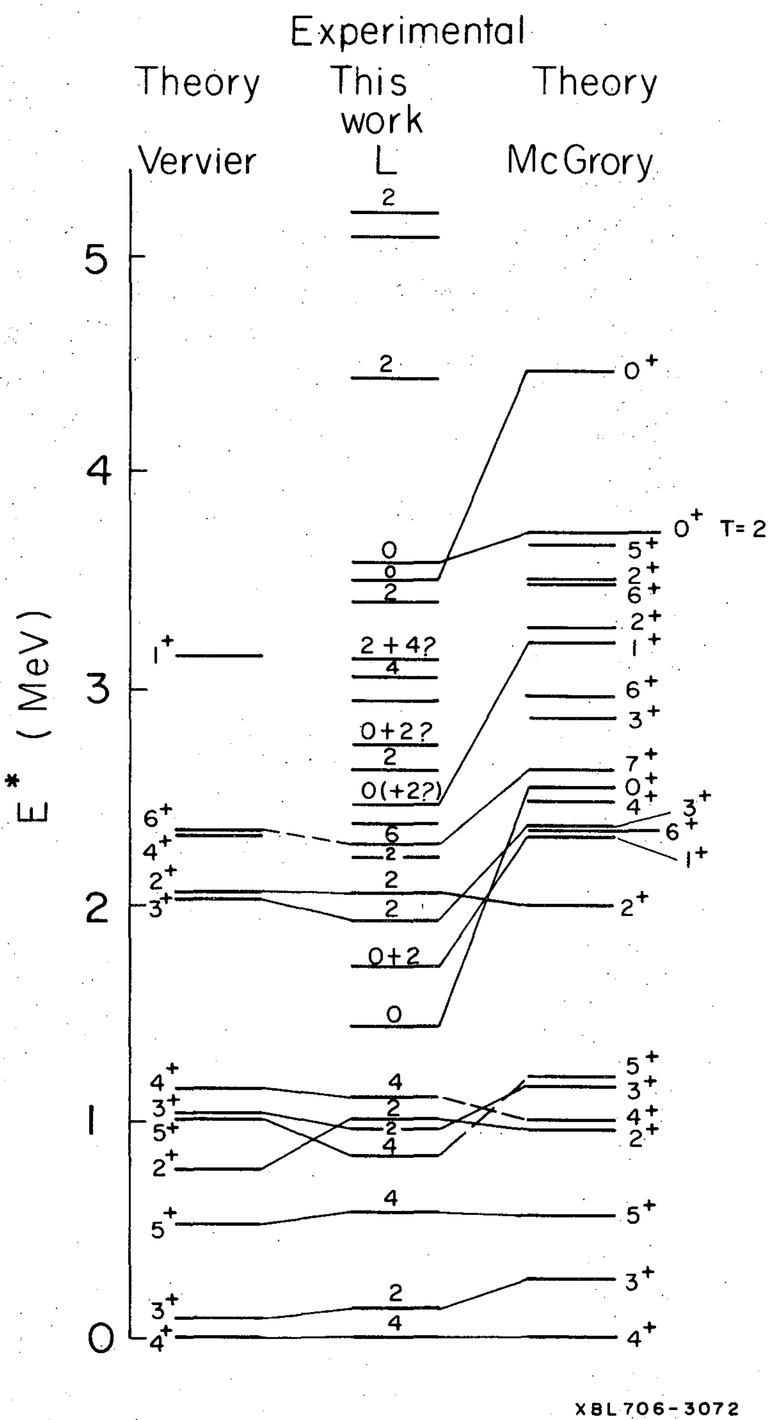
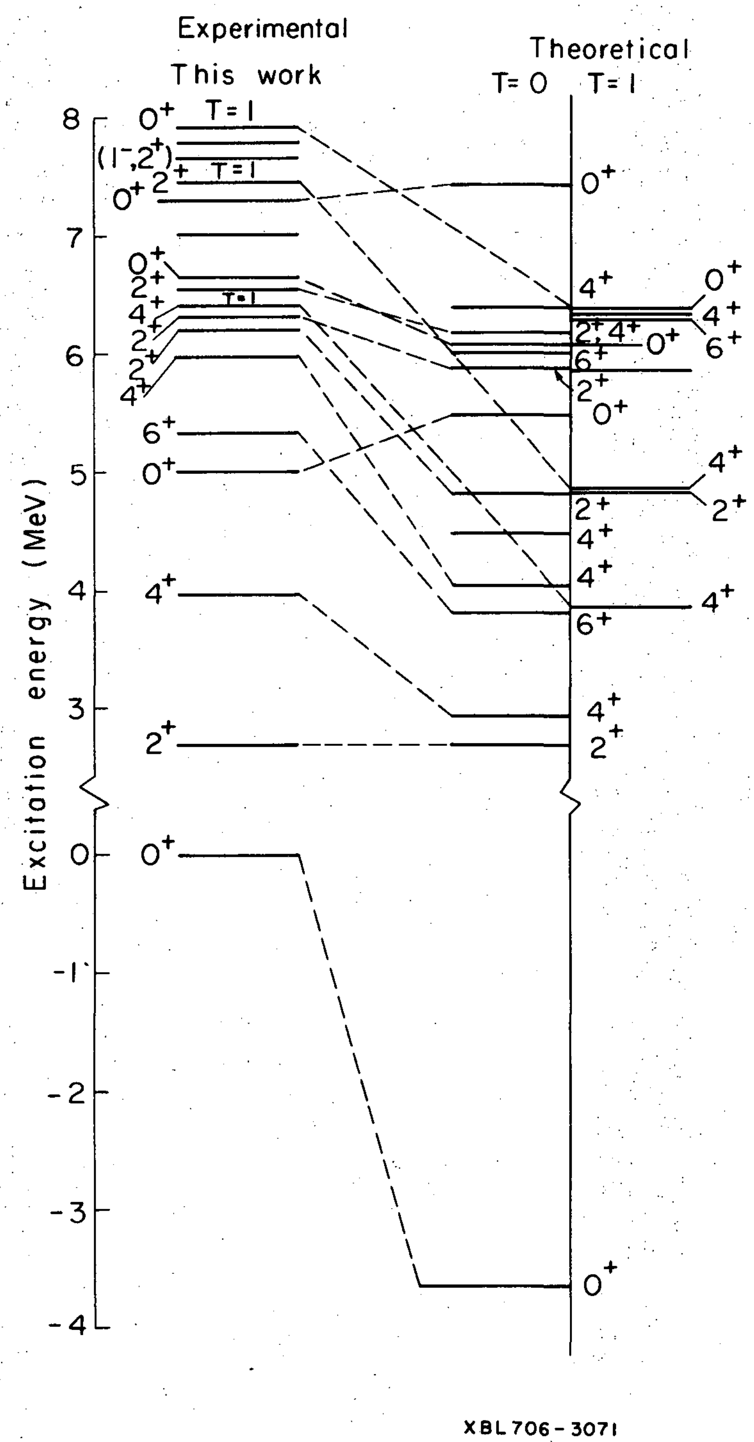
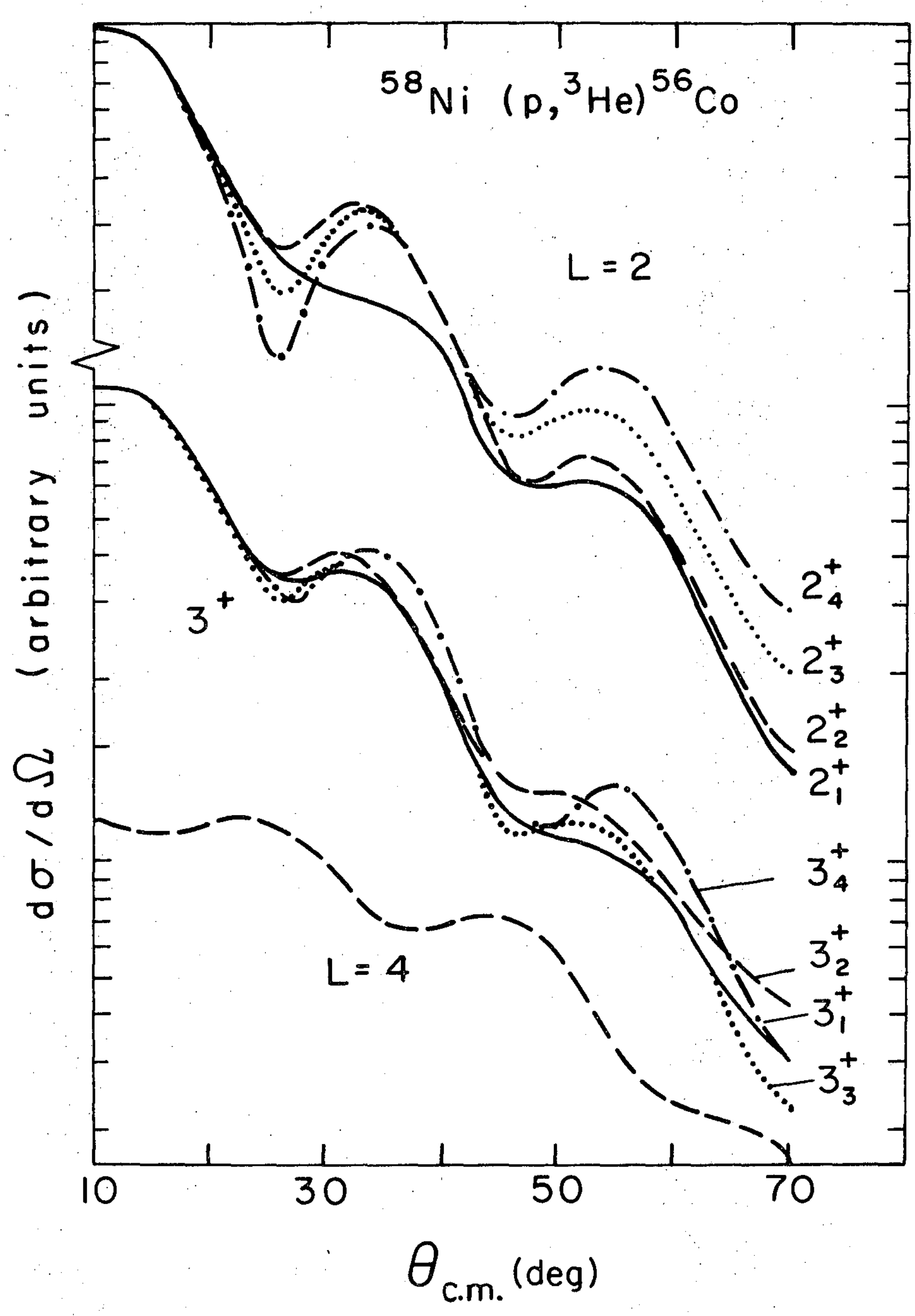

Experimental
Theory
This work
Theory
Vervier
L
McGrory
E* (MeV)
0+ T=2
XBL 706-3072

Fig. 5



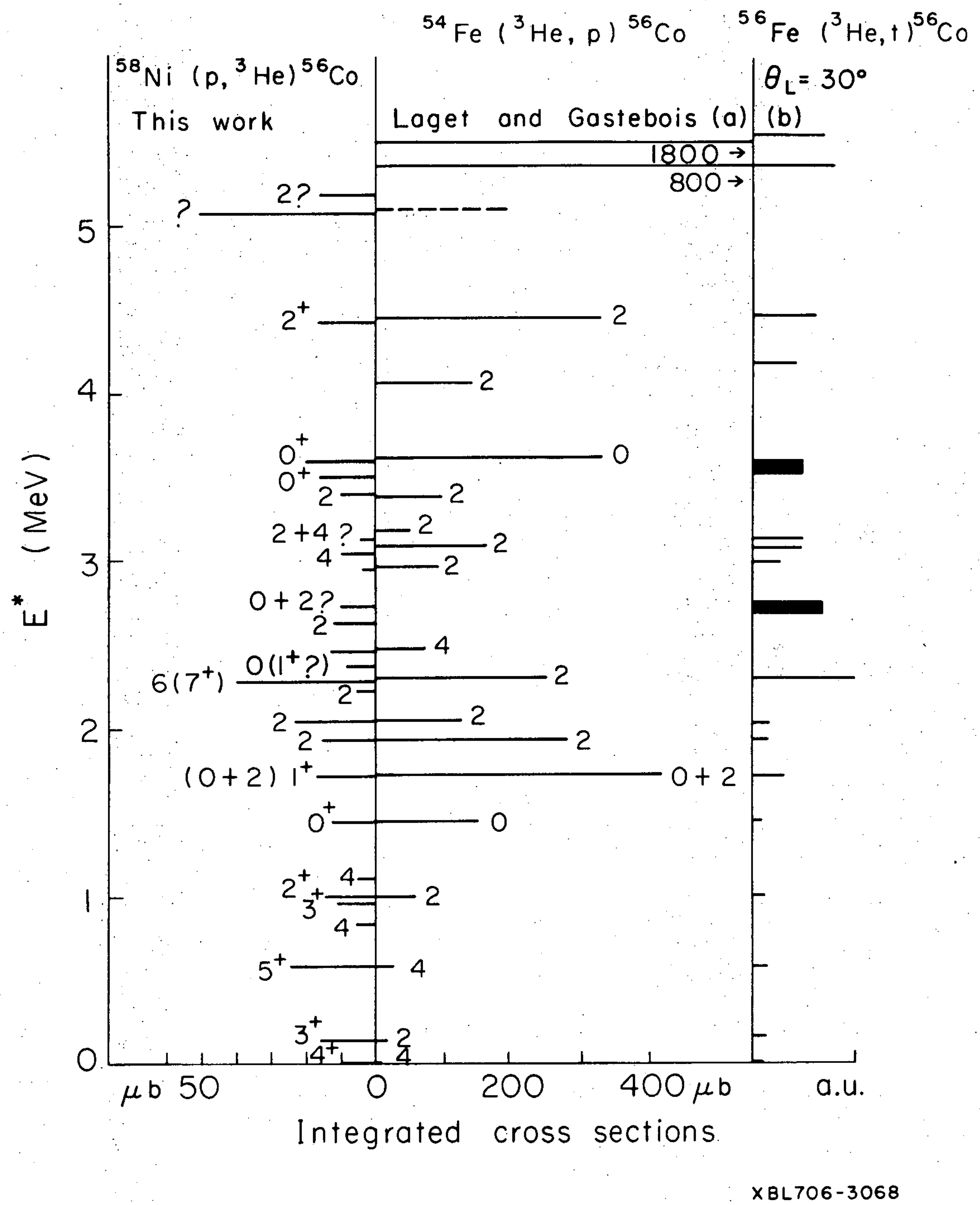
Experimental
This work
Theoretical
T= 0
T= 1
Excitation energy (MeV)
XBL 706-3071

Fig. 6



XBL706-3070

Fig. 7



^{54}Fe (^{3}He, p) ^{56}Co
^{56}Fe (^{3}He, t) ^{56}Co
^{58}Ni (p, ^{3}He) ^{56}Co
This work
Laget and Gastebois (a)
θ_L = 30°
(b)
1800 →
800 →
E* (MeV)
μb 50
0
200
400 μb
a.u.
Integrated cross sections
XBL706-3068

Fig. 8

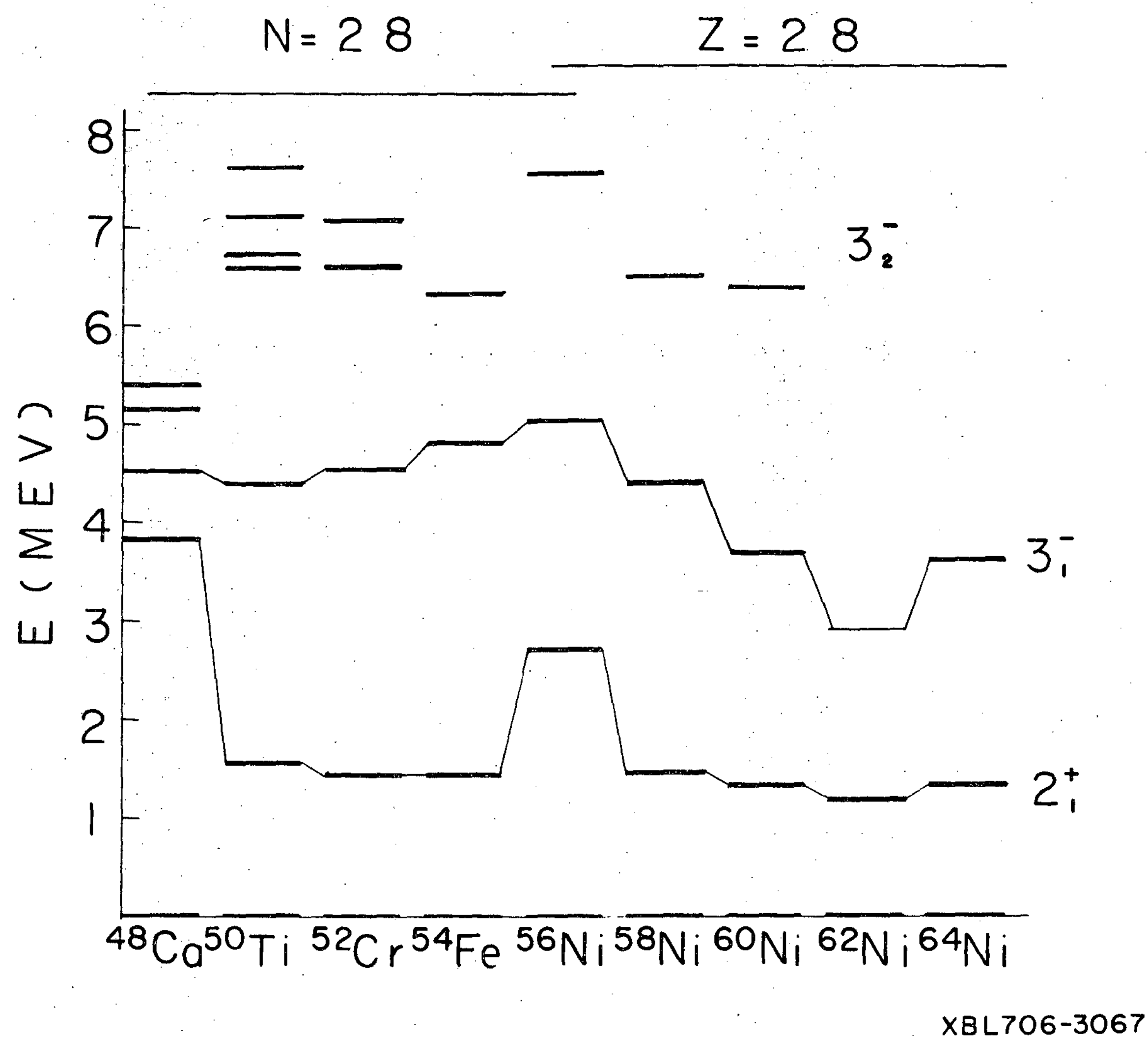

N = 2 8
Z = 2 8
8
7
6
5
4
3
2
1
E (MEV)
3₂⁻
3₁⁻
2₁⁺
48Ca 50Ti 52Cr 54Fe 56Ni 58Ni 60Ni 62Ni 64Ni
XBL706-3067

Fig. 9

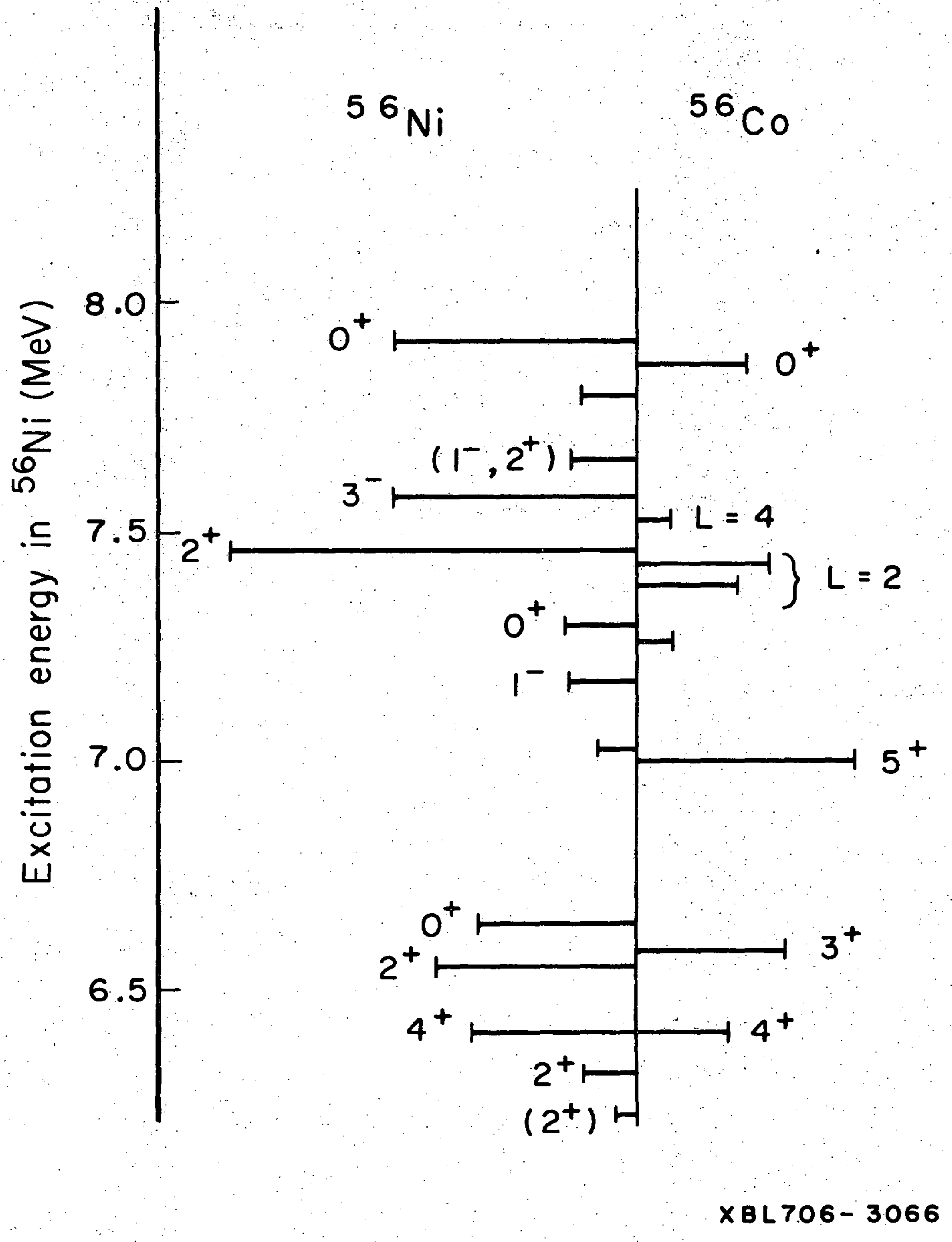

56Ni
56Co
Excitation energy in 56Ni (MeV)
8.0
7.5
7.0
6.5
0+
0+
(1−,2+)
3−
L = 4
2+
L = 2
0+
1−
5+
0+
3+
2+
4+
4+
2+
(2+)
XBL706-3066

Fig. 10

LEGAL NOTICE

TECHNICAL INFORMATION DIVISION
LAWRENCE RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720