Nuclear Physics **A186** (1972) 379—392; © *North-Holland Publishing Co., Amsterdam*

ON THE ^{58}Ni(^{3}He, p)^{60}Cu REACTION

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Received 17 June 1971

Abstract: A shell-model description of ^{58}Ni and ^{60}Ni, ^{60}Cu and ^{60}Zn is attempted on the basis of an inert ^{56}Ni core and two or four valence particles moving in the $p_{\frac{3}{2}}$, $f_{\frac{5}{2}}$ and $p_{\frac{1}{2}}$ shells. The shell-model space is restricted to the lowest-seniority configurations. Energy eigenvalues and angular distributions for the reaction ^{58}Ni(^{3}He, p)^{60}Cu are obtained and compared with available experimental data.

1. Introduction

Some previous shell-model calculations [1-4]) performed for the Ni isotopes were used as benchmarks to test the adequacy of different kinds of two-body residual effective interactions. These calculations take advantage of the fact that the low-lying states of ^{57}Ni are of clear single-particle nature [4]) and therefore the assumption of an inert ^{56}Ni core seams adequate. However, few attempts were made [12, 13]) to analyse within similar assumptions systems that simultaneously include both protons and neutrons.

Little is known so far about the adequacy of $T = 0$ two-body matrix elements of effective interactions. The shell-model studies of doubly odd nuclei in the neighbourhood of a doubly closed-shell nucleus are a suitable tool to study that particular channel of a two-body residual force. The task of fitting the energy spectra of doubly odd nuclei is complicated by the fact that many configurations are not inhibited by the Pauli principle and, therefore, a great density of low-lying states is usually found.

Experiments [5]) on (^{3}He, p) reactions on ^{58}Ni target have added a good deal of information about the ^{60}Cu spectrum to the (p, n) data obtained by Miller and Kavanagh [6]) and Birstein *et al.* [10]). The purpose of the present paper is to perform a shell-model description of the spectrum of ^{60}Cu, together with a DWBA analysis of available angular distributions. With these results, a joint test of $T = 0$ and $T = 1$ matrix elements is subsequently attempted.

The general method of calculation is described in sect. 2 and the results are discussed in sect. 3.

2. Formalism

The shell-model calculation performed in this paper assumes that the ^{56}Ni is an inert core in which both protons and neutrons fill all orbits up to the $1f_{\frac{7}{2}}$.

Within this assumption a suitable shell-model basis to describe the ^{58}Ni and ^{58}Cu low-energy spectra is

$$\Psi^{IT}_{MN}(j_1 j_2) = N^{IT}_{j_1 j_2}[a^+_{j_1} a^+_{j_2}]^{IT}_{MN}|0\rangle,$$
$$N^{IT}_{j_1 j_2} = (1-\delta_{j_1 j_2}(-)^{I+T})^{-\frac{1}{2}}, \qquad \varepsilon_{j_1}; \varepsilon_{j_2} > \varepsilon_{1f\frac{7}{2}}, \tag{1}$$

the operators $a^+_{j_1, m_1, \tau_1,}$ create a nucleon in a state of angular momentum j_1 with projection m_1 and isospin projection τ_1, and ε_j denote the single-particle energies. Square brackets denote both the vector coupling of angular momentum and isospin and $|0\rangle$ denotes the ^{56}Ni ground state.

In order to describe ^{60}Zn, ^{60}Cu or ^{60}Ni one can extend (1) as

$$\Psi^{IT, J_1T_1, J_2T_2}_{j_1j_2j_3j_4} = N^{IT, J_1T_1, J_2T_2}_{j_1j_2j_3j_4}[[a^+_{j_3} a^+_{j_4}]^{J_1T_1}[a^+_{j_1} a^+_{j_2}]^{J_2T_2}]^{IT}|0\rangle. \tag{2}$$

The coefficient N is the corresponding normalization constant. However the full basis (2) was not used in this calculation. Two restrictions were imposed to this shell-model space:

(a) One of the two pairs appearing in (2) was always assumed to be coupled to angular momentum zero, and isospin one, i.e.

$$\Psi^{IT, 01, IT_1}_{j_1j_2j_3j_3} = N^{IT, 01, IT_1}_{j_1j_2j_3}[[a^+_{j_3} a^+_{j_3}]^{01}[a^+_{j_1} a^+_{j_2}]^{IT_1}]^{IT}|0\rangle. \tag{2'}$$

This assumption is consistent with previous shell-model calculations of the Ni isotopes in which it was found that the lowest-seniority configurations accounted for the largest part of the nuclear wave functions.

The use of the shell-model basis (2′) is further justified by its specificity to the (^{3}He, p) transfer reaction whose study is also the aim of this paper.

(b) The four added particles to the ^{56}Ni core were assumed to move only in the $p_{\frac{3}{2}}$, $f_{\frac{5}{2}}$ and $p_{\frac{1}{2}}$ shells. It is therefore unnecessary to carry other quantum numbers different from j while labeling the single-particle states (there are no ambiguities such as those appearing when dealing with a $p_{\frac{1}{2}}$ and an $s_{\frac{1}{2}}$ levels).

The antisymmetry of the four-particle states (2′) is already contained in the anticommutation properties of the nucleon creation operators. However there are still problems when dealing with the basis (2′). In general the wave functions (2′) are not orthogonal with respect to the intermediate isospin quantum number T_1, i.e.:

$$\langle \Psi^{IT, 01, IT_1}_{j_1j_2j_3j_3} | \Psi^{IT, 01, IT'_1}_{j_1j_2j_3j_3} \rangle \neq \delta_{T_1T'_1},$$

therefore an orthonormalization procedure must be carried over, this is a simple task, since only two states with $T_1 = 0, 1$ are involved.

If, in addition, an order is imposed among j_1 and j_2 any possible overcompleteness of the basis is avoided.

Within second quantization notation, a two-body residual interaction can be written

$$W = -\sum_{\substack{j_1 \geqq j_2 \\ j_3 \geqq j_4}} \sum_{J,T} [(2J+1)(2T+1)]^{\frac{1}{2}} \langle \psi^{JT}_{MN}(j_1\, j_2)|V|\psi^{JT}_{MN}(j_3\, j_4)\rangle N^{JT}_{j_1 j_2} N^{JT}_{j_3 j_4} \times [[a^+_{j_1} a^+_{j_2}]^{JT} [\alpha_{j_3} \alpha_{j_4}]^{JT}]^{00}_{00}. \quad (3)$$

The matrix element in (3) is taken between normalized, antisymmetric, two-particle states. The operators $\alpha_{jm\tau}$ are defined by

$$\alpha_{jm\tau} = (-)^{j+\frac{1}{2}-m-\tau} a_{j-m-\tau},$$

and have the suitable transformation properties under rotations in both isospin and spin spaces.

The problem of obtaining the matrix elements of (3) between two wave functions (2′) is reduced to the calculation of a geometric coefficient

$$\mathcal{M} = \langle 0|\{[[a^+_{j_3} a^+_{j_3}]^{01}[a^+_{j_1} a^+_{j_2}]^{IT_1}]^{IT}\}^{\dagger}\{[[a^+_{k_1} a^+_{k_2}]^{AB}[\alpha_{k_3} \alpha_{k_4}]^{AB}]^{00}\} \times \{[[a^+_{j'_3} a^+_{j'_3}]^{01}[a^+_{j'_1} a^+_{j'_2}]^{IT'_1}]^{IT}\}|0\rangle. \quad (4)$$

This can be found to be

$$\begin{aligned}
\mathcal{M} = & -\frac{2}{\sqrt{3}} \delta_{k_1 k_2} \delta_{k_3 j'_3} \delta_{k_4 j'_3} \delta_{A,0} \delta_{B,1} \{(j_3\, j_3)_{01}(j_1\, j_2)_{IT_1}||(k_1\, k_1)_{01}(j'_1\, j'_2)_{IT_1}\}^{IT} \\
& + (-)^{T+T'_1}[(2I+1)(2T'+1)]^{-\frac{1}{2}} \delta_{A,I} \delta_{BT'_1} \Delta^{IT'_1}_{k_3 k_4,\, j'_1 j'_2} \\
& \times \{(j_3\, j_3)_{01}(j_1\, j_2)_{IT_1}||(k_1\, k_2)_{IT'_1}(j'_3\, j'_3)_{01}\}^{IT} \\
& + 2(2j'_3+1)^{-1}[(2B+1)(2I+1)]^{-\frac{1}{2}} \sum_{DC} \mathscr{A} \begin{pmatrix} \frac{1}{2} & \frac{1}{2} & 1 \\ \frac{1}{2} & \frac{1}{2} & T'_1 \\ B & D & T \end{pmatrix} (-)^{I+C+j'_1-j'_3}(2C+1)^{\frac{1}{2}} \\
& \times [U(j'_1\, j'_2\, AC, Ij'_3) \Delta^{AB}_{k_3 k_4,\, j'_3 j'_1} \{(j_3\, j_3)_{01}(j_1\, j_2)_{IT_1}||(k_1\, k_2)_{AB}(j'_3\, j'_2)_{CD}\}^{IT} \\
& + (-)^{T'_1+1} U(j'_2\, j'_1\, AC, Ij'_3) \Delta^{AB}_{k_3 k_4,\, j'_3 j'_2} \{(j_3\, j_3)_{01}(j_1\, j_2)_{IT_1}||(k_1\, k_2)_{AB}(j'_3\, j'_1)_{CD}\}^{IT}],
\end{aligned}$$

$$\Delta^{AB}_{k_1 k_2,\, j_1 j_2} = \delta_{k_1 j_1} \delta_{k_2 j_2} + (-)^{j_1+j_2+A+B} \delta_{k_1 j_2} \delta_{k_2 j_1}. \quad (5)$$

Use has been made of the unitary 6-j and 9-j symbols. The curly brackets $\{||\}$ appearing in (5) are defined by

$$\begin{aligned}
& \{(j_3\, j_3)_{01}(j_1\, j_2)_{IT_1}||(k_1\, k_2)_{AB}(k_3\, k_4)_{CD}\}^{IT} \\
& = \langle 0|\{[[a^+_{j_3} a^+_{j_3}]^{01}[a^+_{j_1} a^+_{j_2}]^{IT_1}]^{IT}\}^{\dagger}\{[[a^+_{k_1} a^+_{k_2}]^{AB}[a^+_{k_3} a^+_{k_4}]^{CD}]^{IT}\}|0\rangle \\
& = 2\delta_{k_1 j_3} \delta_{k_2 j_3} \delta_{A,0} \delta_{B,1} \delta_{C,I} \delta_{T_1,D} \Delta^{IT_1}_{j_1 j_2,\, k_3 k_4} \\
& + (-)^{T+T_1+1} 2\delta_{k_3 j_3} \delta_{k_4 j_3} \delta_{C,0} \delta_{D,1} \delta_{A,I} \delta_{T_1,B} \Delta^{IT_1}_{j_1 j_2,\, k_1 k_2} \\
& - 2\mathscr{A} \begin{pmatrix} \frac{1}{2} & \frac{1}{2} & B \\ \frac{1}{2} & \frac{1}{2} & D \\ 1 & T_1 & T \end{pmatrix} (2A+1)^{\frac{1}{2}}(2j_3+1)^{-\frac{1}{2}} \\
& \times [\delta_{k_1 j_3} \delta_{k_3 j_3} \Delta^{IT_1}_{j_1 j_2,\, k_2 k_4}(2k_2+1)^{-\frac{1}{2}} U(j_3\, k_4\, AI, Ck_2) \\
& + (-)^{k_3+k_4+C+D} \delta_{k_1 j_3} \delta_{k_4 j_3} \Delta^{IT_1}_{j_1 j_2,\, k_2 k_3}(2k_2+1)^{-\frac{1}{2}} U(j_3\, k_3\, AI, Ck_1) \\
& + (-)^{k_1+k_2+A+B} \delta_{k_2 j_3} \delta_{k_4 j_3} \Delta^{IT_1}_{j_1 j_2,\, k_1 k_4}(2k_1+1)^{-\frac{1}{2}} U(j_3\, k_4\, AI, Ck_2) \\
& + (-)^{k_1+k_2+k_3+k_4+A+B+C+D} \delta_{k_2 j_3} \delta_{k_4 j_3} \Delta^{IT_1}_{j_1 j_2,\, k_1 k_3}(2k_1+1)^{-\frac{1}{2}} U(j_3\, k_3\, AI, Ck_1)]. \quad (6)
\end{aligned}$$

The normalization coefficients of (2′) can be obtained as a particular case of (6).

The overlaps (6) also appear in the calculation of the two-body spectroscopic factors for a two-body transfer reaction. The $A = 58$ and $A = 60$ wave functions are written as

$$\psi^{JT}_{(60)} = \sum_{\gamma} c^{(60)}_{\gamma} \mathcal{N}_{\gamma} [[a^{+}_{j_3} a^{+}_{j_3}]^{01} [a^{+}_{j_1} a^{+}_{j_2}]^{JT_1}]^{JT} |0\rangle,$$
$$\psi^{IR}_{(58)} = \sum_{(j'_1 j'_2)} c^{(58)}_{j'_1 j'_2} N^{IR}_{j'_1 j'_2} [a^{+}_{j'_1} a^{+}_{j'_2}]^{IR} |0\rangle, \tag{7}$$

the summation index γ stands for all the quantum numbers that are necessary to label the four-particle states. Within this notation, the spectroscopic factor for transferring a pair of particles with angular momenta $k_1 k_2$ coupled to ΔI and isospin ΔT is

$$S(k_1 k_2, \Delta I \Delta T, IR, JT) = \langle \psi^{JT}_{(60)} [[a^{+}_{k_1} a^{+}_{k_2}]^{\Delta I \Delta T} \psi^{IR}_{(58)}]^{JT} \rangle N^{\Delta I, \Delta T}_{k_1 k_2}$$
$$= \sum_{\gamma (j'_1 j'_2)} c^{(60)}_{\gamma} c^{(58)}_{(j'_1 j'_2)} \mathcal{N}_{\gamma} N^{\Delta I \Delta T}_{k_1 k_2} N^{IR}_{j'_1 j'_2} \{ (j_3\, j_3)_{01} (j_1\, j_2)_{JT_1} || (k_1\, k_2)_{\Delta I, \Delta T} (j'_1 j'_2)_{IR} \}. \tag{8}$$

In this particular case, ^{58}Ni is the only possible stable $A = 58$ target, whose ground state is a 0^+. For this case the following sum rule for the spectroscopic factors can be proven to be valid, and may be used for checking numerical calculations:

$$\sum_{T_f} S(j_1 j_2, I \Delta T, 01, I T_f) S(j_3 j_4, I \Delta T, 01, I T_f) \langle \Delta T 1 N 1 | T_f\, N+1 \rangle^2 [N^{I \Delta T}_{j_1 j_2} N^{I \Delta T}_{j_3 j_4}]^{-1}$$
$$= c^{(58)}_{j_2 j_2} c^{(58)}_{j_4 j_4} \delta_{j_1 j_2} \delta_{j_3 j_4} \delta_{I,0} \delta_{\Delta T, 1} + \left\{ 1 - \langle \tfrac{1}{2} \tfrac{1}{2} \tfrac{1}{2} N - \tfrac{1}{2} | \Delta T N \rangle \left[\frac{c^{(58)2}_{j_1 j_1}}{j_1 + \frac{1}{2}} + \frac{c^{(58)2}_{j_2 j_2}}{j_2 + \frac{1}{2}} \right] \right\} \Delta^{I, \Delta T}_{j_1 j_2, j_3 j_4}. \tag{9}$$

3. Calculations

By using the method described in sect. 2, it is possible to calculate the energy spectra of ^{58,60}Ni, ^{58,60}Cu and ^{60}Zn.

In this calculation three different sets of $T = 1$, two-body matrix elements were used. The first was taken from ref. [2]) (here, on the AU interaction). In this reference some of the matrix elements were adjusted in order to fit experimental data and some others were derived using a Kallio-Kolltveit potential. The second set was taken from ref. [3]) (here, on AR interaction). It was obtained by performing a least-square fit of the experimental data with an eight adjustable parameter, two-body effective interaction. The third set (here on K-interaction) was obtained from reaction matrix theory by Kuo and Macfarlane [7]) and is the only one that also provides values for the $T = 0$ channel of the two-body interaction. The two previous sets of matrix elements are combined with this $T = 0$ set, to perform the Cu and Zn calculations.

The single-particle energies were fixed at $\varepsilon(2p_{\frac{3}{2}}) = 0.0$, $\varepsilon(1f_{\frac{5}{2}}) = 0.78$ MeV and $\varepsilon(2p_{\frac{1}{2}}) = 1.08$ MeV as in refs. [2,3]) and related works.

In order to check the adequacy of this treatment, the spectrum of ^{60}Ni was obtained and compared to the more accurate results of refs. [2,3]).

The departures from more exact calculations are listed in table 1; these, in general, depend both on the angular momentum and on the kind of interaction used. It follows also from table 1 that the Auerbach interaction tends to favour lower-seniority configurations, and therefore is more suitable for our purposes.

TABLE 1

Comparison of ^{60}Ni energy spectrum obtained within this calculation with that reported in refs. [3,4]).

	Argonne interaction			Auerbach interaction		
J	this calc.	ref. [3])	departure (%)	this calc.	ref. [2])	departure (%)
	0.00	0.0		0.0	0.0	
0	2.41	2.32	4	2.34	2.27	3
	3.41	3.27	4	3.12	2.98	5
1	4.59	3.45	33	4.04	3.81	6
	1.57	1.42	10	1.78	1.55	15
2	2.20	2.17	1	2.55	2.36	8
	2.86	2.58	11	2.99	2.88	4
3	3.41	2.75	24	3.38	2.99	13
	2.53	2.20	15	2.52	2.50	1
	3.10	2.80	11	3.64	3.02	20
			av. 12.6			av. 8.3

An additional check of this calculation is to study the ground state energies of ^{58}Ni and ^{60}Ni. These come out to be (in MeV) 22.3 and 43.98 (K-interaction), 22.6 and 43.14 (AU interaction), 22.56 and 42.86 (AR interaction) which are in general agreement with the experimental values 22.45 and 42.84 for the ^{58}Ni and ^{60}Ni respectively. The theoretical values obtained in ref. [4]) are 22.44 and 42.85; those of ref. [3]) are 22.56 and 42.88. Unfortunately a similar comparison cannot be carried over for the $^{58,60}Cu$ and ^{60}Zn ground states. This is due to the fact that no information is available for the binding energy of ^{57}Cu which would provide the proton separation energy of the ^{56}Ni core. However the position of the ground states of $^{58,60}Cu$ with respect to those of the Ni isotopes can be checked from the position of the corresponding analogue states.

These departures, together with a comparison of theoretical and experimental results in fig. 1, suggest that one can be rather confident that the gross features will be reproduced. It must however be pointed out, that the validity of neglecting higher-seniority configurations may not be as adequate when dealing with non-identical particles, such as in ^{60}Cu or ^{60}Zn.

The experimental evidence [6]) provided by a $^{58}Ni(^{3}He, n)^{60}Zn$ reaction is compared with theoretical results in fig. 2. All three forces predict a first 2^{+} excited state in ^{60}Zn, in agreement with the systematics of doubly even nuclei but the AR interaction is the only one that yields the correct excitation energy.

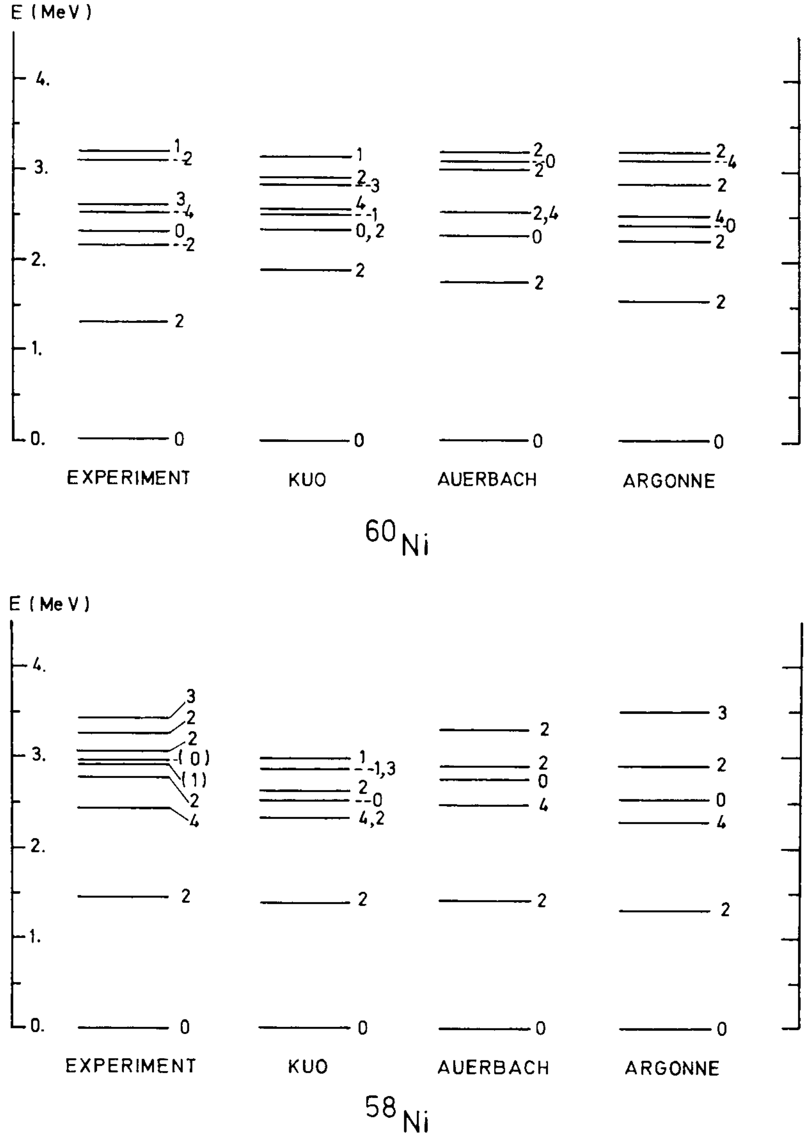

Fig. 1. Experimental and theoretical energy spectra of ^{58}Ni and ^{60}Ni. The different theoretical results are obtained with the present shell-model calculation and using the two-body residual forces of Kuo, Auerbach and Cohen (Argonne group) as explained in the text.

In the ^{58}Cu spectrum of fig. 3, the $T = 0$ states are the same for the three cases, since all three interactions are the same as described above.

However the position of the isobaric analogue of ^{58}Ni ground and excited states differs from one case to the other. The relative strength of the $T = 0$ and $T = 1$ channels seems to be better fitted by the AR interaction. This feature is also checked in the

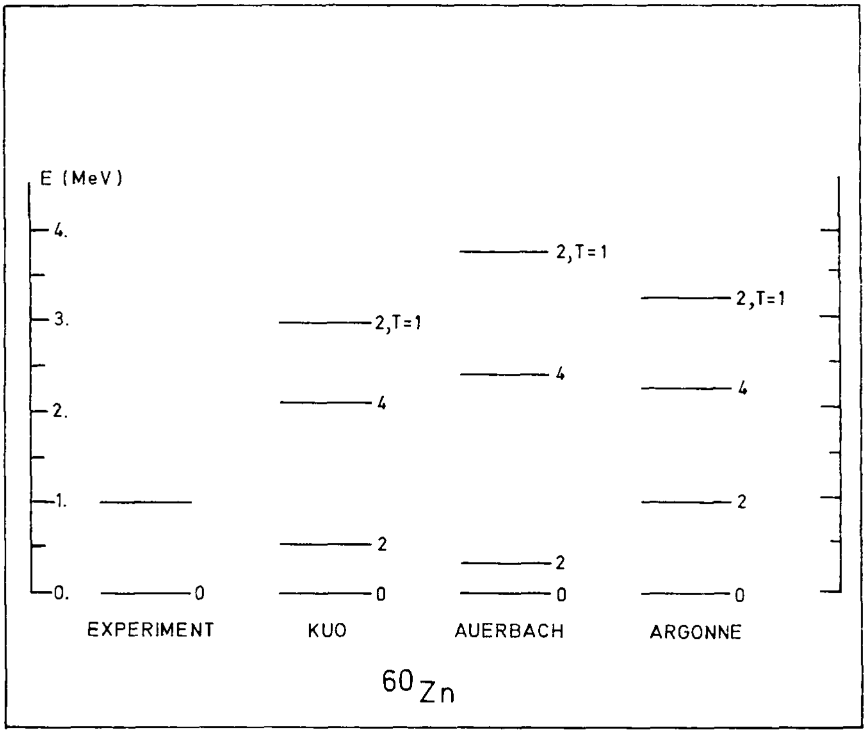

Fig. 2. Energy spectra of ^{60}Zn. Experimental evidence is taken from ref. [6]). The only level plotted above the $J = 4$ is the analogue of ^{60}Cu.

^{60}Cu spectrum. The analogue states of ^{58}Ni are too high and those of ^{60}Ni too low when obtained with the K-interaction. The AU interaction provides values that are consistently too low in both cases.

Regarding the $T = 1$ states in ^{60}Cu, all three forces succeed in giving a $J = 2^+$ ground state and a first excited 1^+ but all of them fail to reproduce the right density of states below 1 MeV, the AR interaction being the worst of them all.

The experiment of ref. [5]) does not provide information upon a 0.332 MeV level reported in ref. [10]). No theoretical evidence is obtained within this calculation about a low-lying level with small (^{3}He, p) strength that could have not be seen in this reaction.

In addition to the shell-model calculation, a DWBA analysis was performed for the transitions to the lowest states of each spin and to the analogue states. All the experimental information was taken from the ^{58}Ni(^{3}He, p)^{60}Cu reaction [5,11]). The optical parameters that were used are listed in table 3 [ref. [8])].

The reaction under consideration can in general proceed with an isospin transfer of 0 or 1. However certain states can only be populated via one of the two channels. The $J = 0$, $T = 1$ states and all the $T = 2$ states are excited with an isospin transfer

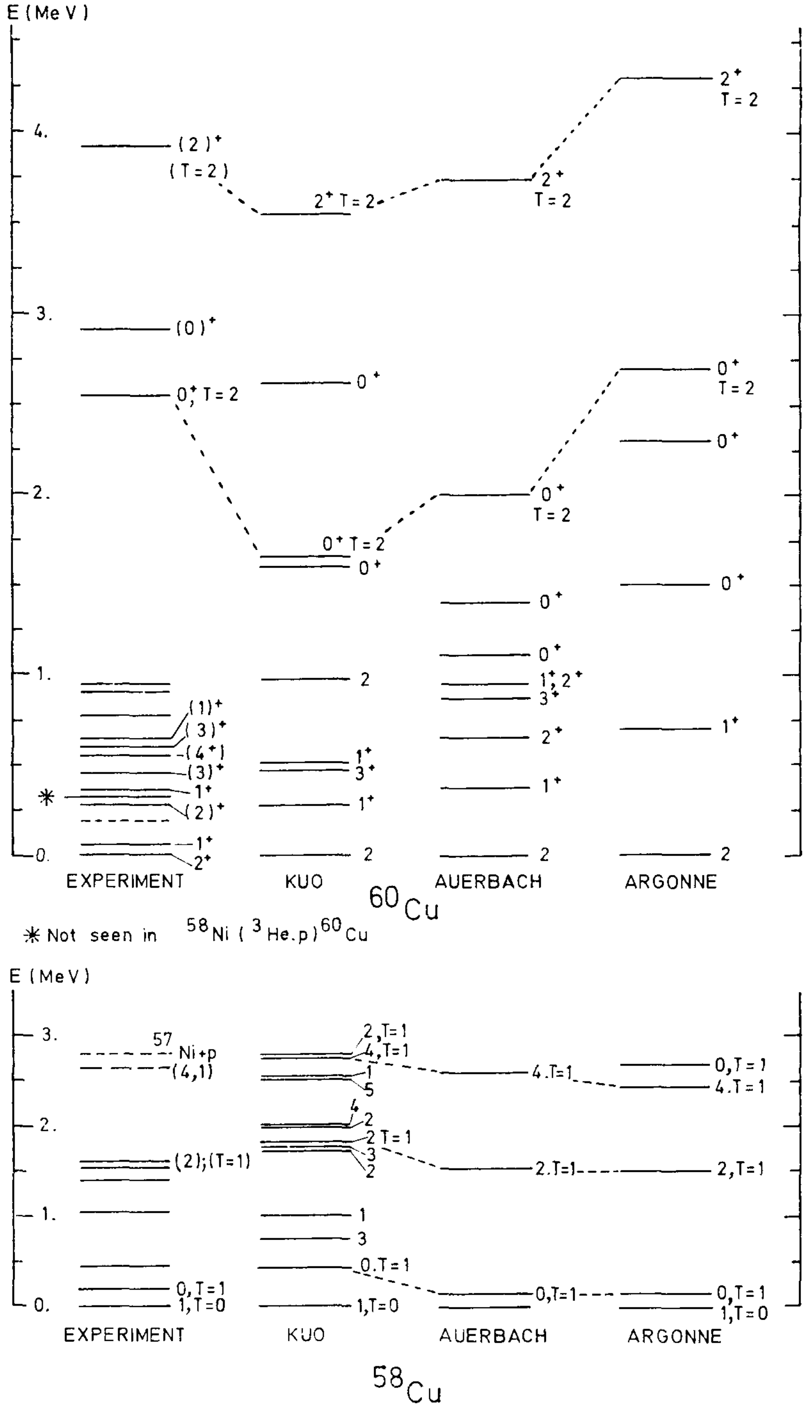

Fig. 3. Energy spectra of ^{58}Cu and ^{60}Cu. For the latter only states below 1 MeV and the two analogue states are plotted. This figure also shows the tentative 0^+ $T = 1$ state and the corresponding theoretical results for the 0^+ $T = 1$ states.

of $\Delta T = 1$. On the other hand, since no parity change is found, all odd-J states with $T = 1$ are populated with $\Delta T = 0$. Only the states having $J = 2$, 4 and $T = 1$ will present admixtures of both channels.

In principle, both channels will have different statistical factors, these being dependent on the spin dependence of the nucleon-nucleon interaction between the outcoming proton and the stripped nucleons [14]). This amounts to giving different normalizations to the singlet spin ($\Delta T = 1$) and to the triplet spin ($\Delta T = 0$) transfers. The population of all odd-J states will then be normalized by a factor equal to the relative strengths of the $\Delta T = 0$ and $\Delta T = 1$ channels. The relative strength can be estimated by comparing the population of the $J = 0$, $T = 2$ and the $J = 1, 3$, $T = 1$ and comes out to be of the order of unity. In all other cases but one, in which both channels are present ($J = 2, 4$, $T = 1$), it is found that the $T = 1$ and $T = 0$ contributions differ by at least two orders of magnitude and will therefore be insensitive to any realistic change in the above-mentioned normalizations. The analysis of the single case in which both contributions are comparable (ground state, AU interaction) supports the choice of equal strengths. The overall fitting, in addition, is not good enough to favour a detailed study of these statistical factors.

TABLE 2

Experimental and theoretical results of the DWBA analysis of the two analogue states and the lowest $T = 1$ states in ^{60}Cu

State	Experiment		K-interaction		AU interaction		AR interaction	
J; T	E (MeV)	α	E_{th} (MeV)	α	E_{th} (MeV)	α	E_{th} (MeV)	α
0; 2	2.536	1 (7.5°)	1.66	1	1.98	1	2.72	1
(2); (2)	3.874	0.21 (22.5°)	3.56	0.09	3.75	0.52	4.29	0.18
2; 1	0.00	0.09 (22.5°)	0.00	0.16	0.00	0.04		
1; 1	0.058	0.33 (7.5°)	0.280		0.380	0.37		
(2); 1	0.287	0.05 (22.5°)	0.86	0.16	0.67	0.37		
(3); 1	0.452	0.15 (22.5°)	0.480	0.61	0.88	0.41		
(4); 1	0.558	0.04 (45°)	1.53	0.07	0.83	0.07		
(0); 1	2.915	0.11 (7.5°)	1.59	0.03	1.12	0.08		
			2.63	0.18	1.41	0.15		

The coefficient α is the ratio $(d\sigma/d\Omega)^{J,T}_{max.}/(d\sigma/d\Omega)^{0;2}_{max.}$. Below the value of α for each state is given (in brackets) also the angle at which that ratio is taken experimentally.

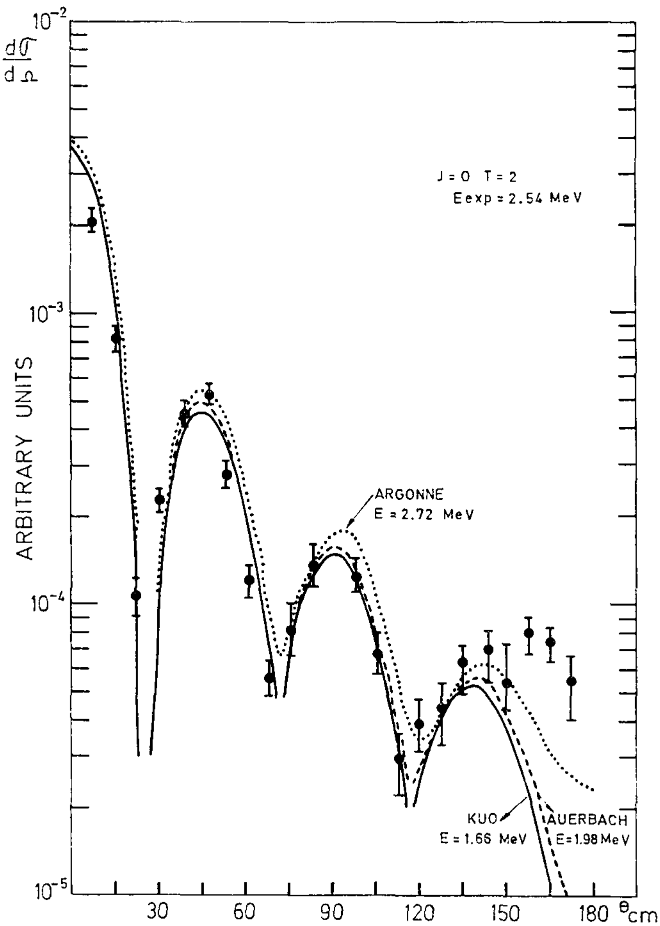

Fig. 4. Experimental and theoretical angular distributions for the $J = 0$ and $T = 2$ state. An overall normalization constant is chosen so to give the best visual fit to experimental values.

The experimental evidence is quite conclusive in locating the $J = 0$, $T = 2$ state at 2.536 MeV and strongly suggests that the 3.874 MeV state has a $J = 2$, and is the analogue of the first excited state of ^{60}Ni.

TABLE 3

Optical parameters used in the DWBA calculations

	Real part			Volume absorption			Surface absorption		
	R_0	a	V	R'_0	a'	W'	R''_0	a''	W''
proton	1.25	0.65	53.0				1.25	0.47	15.5
^{3}He	1.14	0.723	177.0	1.6	0.81	35.0			

In figs. 4 and 5 the corresponding experimental angular distributions are fitted by the theory. The shapes are very well reproduced although the relative strengths leave something to be desired (cf. table 2). The AR interaction provides the ratio of (^{3}He, p) strengths that is closest to experimental values.

For the description of the analogue state only the $T = 1$ matrix elements are involved. Therefore the agreement of the theoretical and experimental results is not surprising. Anyhow it is gratifying that the adequacy of those effective interactions is preserved when dealing with an (^{3}He, p) reaction.

In what follows the results for different $T = 1$ states is discussed. The AR interaction has been excluded from this discussion due to the large departures between the theoretical and experimental energies.

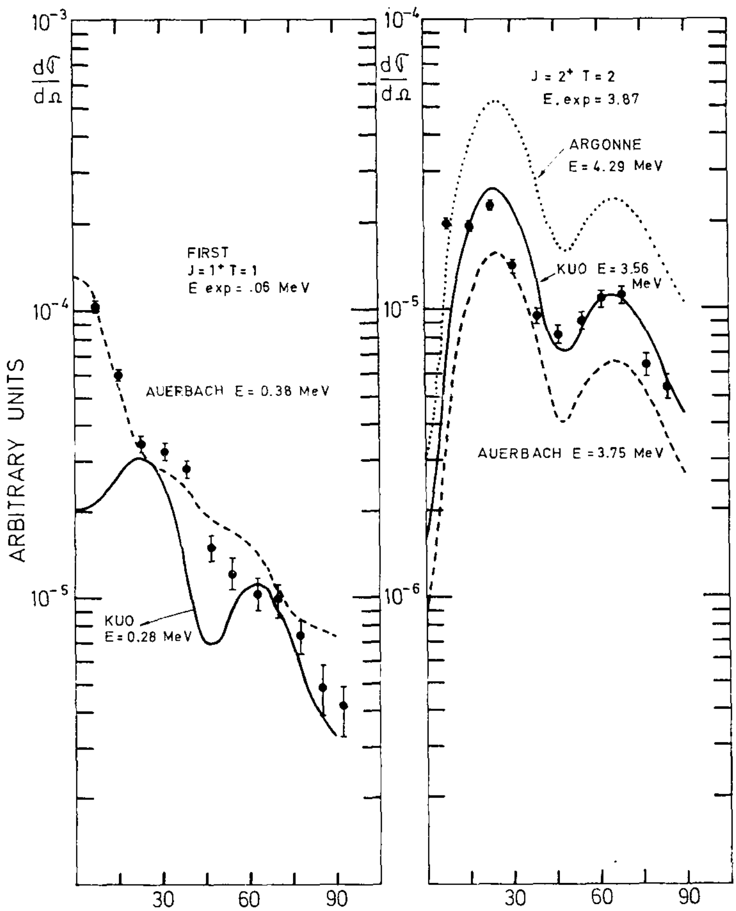

Fig. 5. Right: Experimental and theoretical angular distributions for the tentative $J = 2$, $T = 2$ state. A normalization constant is chosen so to adjust the theoretical result obtained with the K-interaction. Relative strengths are discussed in table 2. Left: Angular distributions for the first 1^+ state. The AU angular distribution is the only that displays a strongly mixed $L = 0$ and $L = 2$ shape.

The $J = 1^+$ states. Experimentally $J = 1^+$ states are reported at 0.058, 0.361 and 0.667 MeV. All show angular distributions with strongly mixed $L = 0$ and $L = 2$ components. The 0.361 level is less populated than the others.

Theoretically, the lowest $J = 1^+$ state appears too high. The AU interaction is the only one that succeeds in reproducing a strongly mixed $L = 0$ and $L = 2$ pattern (fig. 5), and in addition provides a reasonable relative strength with respect to the $J = 0$, $T = 2$ state. The rest of the theoretical $J = 1$ states do not follow the experimental pattern of the relative strengths, and in addition, angular distributions show an almost pure $L = 2$ shape. It must however be pointed out that the overlap of the two $J = 1$ wave functions as obtained with the K and AU interactions is 89 %, and that of the ^{58}Ni ground state is 99.8 %. The shape of the angular distributions therefore strongly depend on the detailed structure of the wave functions.

The $J = 2^+$ states. Aside from the ground state, one tentative $J = 2^+$ state is reported at 0.29 MeV.

Ground state wave functions with the K and AU interactions are quite different, overlapping in only 65 %. In this case, this fact is not reflected in the shapes (fig. 6) of the angular distributions since both are pure $L = 2$; this is instead shown by the relative strengths. Greater differences between the theoretical and experimental results appear for the second $J = 2$ state (cf. table 2).

The $J = 3^+$ states. Two $J = 3^+$ states are measured at 0.452 and 0.597 MeV, the higher in energy being populated with a strength that is roughly $\frac{1}{2}$ of the lowest. Angular distributions are pretty pure $L = 2$ shapes. This last fact is obtained also theoretically (fig. 6); the lowest $J = 3^+$ state appears at 0.48 MeV for the K-interaction and at 0.88 MeV for the AU interaction. Relative strengths with respect of the $J = 0$, $T = 2$ state are overestimated by the theory. This may be due to the reduction of the shell-model space that avoids the spreading of the strength over many other components of the wave function that are not specific to the (^{3}He, p) reaction.

The $J = 4^+$ states. One tentative $J = 4$ state is reported at 0.558 MeV. The corresponding theoretical result using both the K and AU interactions is too high. However the strength with which it is populated, when calculated with either of these interactions, is in good agreement with the experimental value (table 2). The shape of the angular distribution is also well reproduced (fig. 6).

The $J = 0^+$ states. The $J = 0^+$ states appear at a high energy, and only two such states are obtained within this shell-model calculation. These appear at 1.59 (1.12) and 2.63(1.41) MeV for the K (AU) interaction. Both results agree that the lowest will appear weaker than the $J = 0$, $T = 2$ state, while the higher in energy will have about 1/5 the strength of the isobaric analogue state.

Experimentally there is a tentative assignment of $J = 0$ to the level at 2.91 MeV having these properties. Within a pairing vibration scheme [9]) a $J = 0$ state would appear at about that energy. The phonon structure of this state would be predomi-

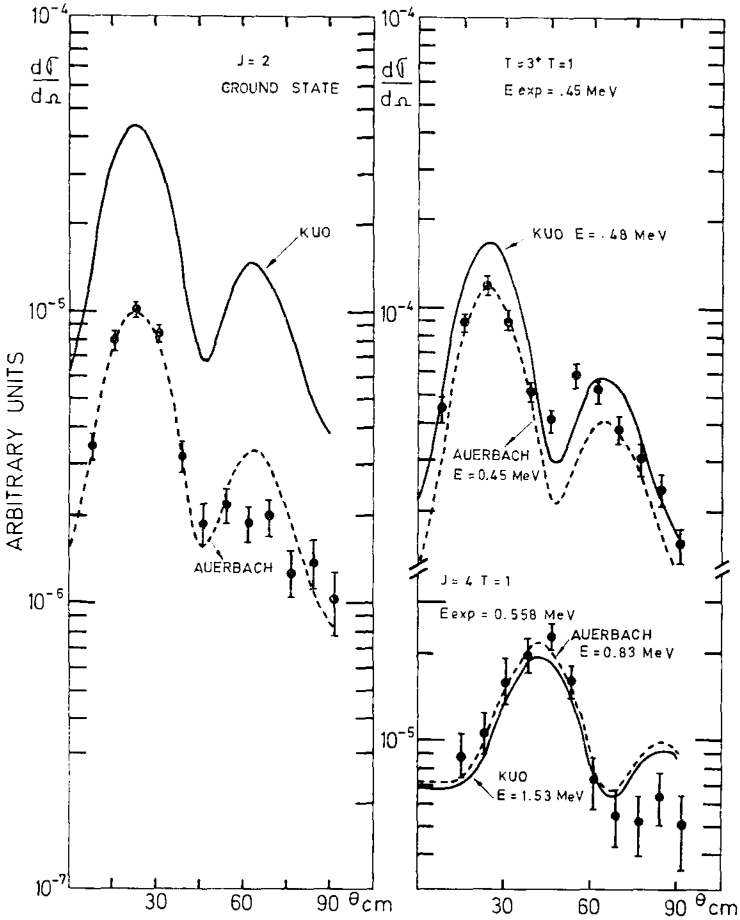

Fig. 6. Experimental and theoretical angular distributions of the lowest $J = 3^+$ and $J = 4^+$ states (right) and of the $J = 2^+$ ground state (left).

nately a $(n_r, t_r;\ n_a, t_a;\ TT_z) = (1, 1;\ 3, 3;\ 1, 1)$ that is different from the one provided by this shell-model calculation since no excitations are assumed in the ^{56}Ni core. (Within a pairing-like description the present structure of that state would correspond to two addition, non-adiabatic pairing phonons.) The (^3He, p) strength to populate the (1, 1; 3, 3; 1, 1) state from the (0, 0; 2, 2; 2, 2), will depend critically on the value of the pairing coupling constant, being very small for any value outside the transition region from the normal to the superconducting phases †.

Which picture is closer to the real physical situation is something that cannot be established with the presently available data. However the fact that core excitations with the same spin and parity can exist close to the predicted 0^+ energy may cast some doubt upon the adequacy of our assumption of an inert ^{56}Ni core.

† There is some evidence that this is precisely the case for this region of the periodic table [9]).

4. Conclusions

The different procedures of refs. [1-4]) give sets of $T = 1$ matrix elements that are consistent with each other and can be considered equally efficient in fitting the experimental data of the Ni isotopes. Yet when combined with a unique set of $T = 0$ matrix elements they yield results that are quite different from each other and the fitting achieved is far from being as satisfactory as the ones obtained with the $T = 1$ channel alone. However general experimental trends regarding (^{3}He, p) relative strengths tend to be reproduced.

The limitation imposed on the shell-model space, keeping only the lowest-seniority configurations, although specific to the analysis of the (^{3}He, p) reaction will tend to overestimate the relative strengths. This can be understood by realizing that in a more general calculation the wave function will be spread over more components that do not have any parentage with that of the ^{58}Ni ground state. As far as the energy spectrum is concerned, that seems to be a drastic limitation. The better low-energy fitting obtained in ref. [12]) can be considered as evidence in favour of this conclusion.

A further question that has to be answered has to do with the relative strengths of the $T = 0$ and $T = 1$ matrix elements that can change the position of the analogue states. In this respect the AR interaction is slightly better than the others because both the position and relative strengths of both states is reasonably fitted. In addition the only experimental evidence on ^{60}Zn is well reproduced. On the other hand the density of the low-lying $T = 1$ states is better given by the K and AU interactions.

The author wishes to thank Dr. B. Bayman for his invaluable help throughout this work and for making available the TWOPAR code to perform the DWBA analysis. He is also indebted to H. J. Young and J. Rapaport for providing all the experimental information and to Dr. D. R. Bès for helpful discussions and encouragement.

References

1) R. D. Lawson, M. H. Macfarlane and T. T. S. Kuo, Phys. Lett. **22** (1966) 168
2) N. Auerbach, Nucl. Phys. **76** (1966) 321; Phys. Lett. **21** (1966) 57
3) S. Cohen *et al.*, Phys. Rev. **160** (1967) 903
4) N. Auerbach, Phys. Rev. **163** (1967) 1203
5) H. J. Young and J. Rapaport, Phys. Lett. **26B** (1968) 143
6) R. G. Miller and R. W. Kavanagh, Nucl. Phys. **A94** (1967) 261
7) T. T. S. Kuo and M. H. Macfarlane, private communication
8) E. F. Gibson *et al.*, Phys. Rev. **155** (1967) 119
R. A. Broglia *et al.*, Nucl. Phys. **A106** (1968) 421
9) B. Bayman, D. R. Bès and R. Broglia, Phys. Rev. Lett. **23** (1969) 1299
10) L. Birstein, Ch. Drory, A. A. Jaffe and Y. Zioni, Nucl. Phys. **A97** (1967) 203
11) H. Young and J. Rapaport, private communication
12) R. P. Singh and M. L. Rustgi, Phys. Rev. **C3** (1971) 1172
13) E. A. Phillips and A. D. Jackson, Jr., Phys. Rev. **169** (1968) 917
14) D. G. Flemming, J. Cerny and N. K. Glendenning, Phys. Rev. **165** (1968) 1153;
D. G. Flemming, J. Cerny, C. C. Maples and N. K. Glendenning, Phys. Rev. **166** (1968) 1012