Energy dependence of 1^+ spin excitations in ^{28}Si

A. Willis,[(1)] M. Morlet,[(1)] N. Marty,[(1)] C. Djalali,[(1,2)] J. Guillot,[(1)] H. Langevin-Joliot,[(1)]
J. Van de Wiele,[(1)] A. Mack,[(1)*] B. Bonin,[(3)] R. Fergerson,[(3)] E. Tomasi-Gustafsson,[(3)] J. C. Lugol,[(3)]
J. C. Duchazeaubeneix,[(4)] and H. Sakaguchi[(3)†]
[(1)]*Institut de Physique Nucleaire, Boite Postale No. 1, 91406 Orsay, France*
[(2)]*Department of Physics and Astronomy, University of South Carolina, Columbia, South Carolina 29208*
[(3)]*Département de Physique Nucléaire—Moyenne Energie, CEN Saclay, 91191 Gif-sur-Yvette CEDEX, France*
[(4)]*Laboratoire National Saturne (LNS), CEN Saclay, 91191 Gif-sur-Yvette CEDEX, France*
(Received 6 February 1990)

Forward-angle cross sections and analyzing powers for the main 1^+ $T=1$ and 1^+ $T=0$ states in ^{28}Si have been measured by proton inelastic scattering at 200, 400, and 600 MeV bombarding energy. The results are compared with microscopic distorted-wave impulse approximation (DWIA) calculations. The sensitivity to the optical potentials is pointed out. Two DWIA methods give compatible results for the $\Delta T=1$ transition at 200 and 400 MeV, but differ strongly for the $\Delta T=0$ transition at 200 MeV. For both the $\Delta T=0$ and the $\Delta T=1$ transitions no clear dependence on the incident energy can be ascertained for the ratio of the experimental to the theoretical cross section.

I. INTRODUCTION

During the last ten years, spin interactions in nuclei have been the subject of much theoretical as well as experimental work.[1] Gamow-Teller transitions (GT) (which involve exchanges of one unit of spin and isospin) are strongly excited in a large number of nuclei by intermediate-energy charge-exchange reactions. The analogues of these transitions are also observed in (p,p'), (e,e'), and (γ,γ') scattering. Much of the recent interest results from the discrepancy between the predicted and the observed strength. Generally, more strength is predicted than is observed experimentally, therefore the discrepancy is referred to as quenching. The observed quenching for these transitions is not fully understood and differences appear between quenchings measured in different experiments.[2] A large number of theoretical and experimental papers have addressed these issues.

Another interesting feature of spin-flip transitions is the energy dependence of their excitation. For a given transition, the evolution of the measured cross section as a function of the bombarding energy is directly related to the energy dependence of the effective part of the nucleon-nucleon interaction responsible for the transition.

The isovector spin-flip component of the effective nucleon-nucleon interaction, which is long range due to pion exchange, is considered as well known. The dependence of this interaction as a function of the bombarding proton energy has been studied in (p,n) reactions by measuring the cross section for the GT transition at 3.95 MeV in ^{14}C(p,n). The GT cross section extrapolated to a momentum transfer $q\sim 0$ is constant within the error bars between 120 and 450 MeV incident energies.[3,4] This constant behavior of the cross section is well reproduced by the different calculations[5,6] using either the free t matrix of Franey and Love[7] derived from the Arndt phase shifts[8] or the G matrices derived from the Paris[9] or the Bonn potential.[10] It is shown also in Ref. 6 that the central part of the spin-isospin interaction $G_{\sigma\tau}$ is nearly density independent for the Bonn potential. Data obtained in (p,p') scattering on ^{28}Si (Ref. 11) for exciting the 1^+ $T=1$ state at 11.45 MeV show that the cross section at small q can be considered as independent of the proton bombarding energy T_p between 200 and 400 MeV.

In contrast with the isovector spin-flip component of the nucleon-nucleon interaction, the isoscalar spin-flip component is considered as poorly known.[12,13] It is a short-range interaction and in nuclear matter G matrices are expected to be density dependent. Experimentally, very few pure isoscalar spin-flip transitions have been studied since charge-exchange reactions are purely isovector and electromagnetic reactions are by far dominated by the isovector part of the electromagnetic interaction. In fact, pure isoscalar spin-flip transitions have recently only been studied in some $N=Z$ nuclei by proton inelastic scattering.[2] Inelastic proton scattering on ^{28}Si has found that, for the 1^+ $T=0$ state at 9.50 MeV, the ratio of the experimental to the theoretical cross section[11] is energy dependent and increases between 200 and 400 MeV more rapidly than predicted by the Franey and Love t matrix.

In order to get a better understanding of the energy dependence of the excitation of 1^+ spin-flip transitions and to extend the existing data to higher proton bombarding energies T_p, we have studied the excitation of the 1^+ $T=0$ and 1 states located, respectively, at 9.50 and 11.45 MeV in ^{28}Si at $T_p=200$, 400, 600, and 800 MeV. The results are compared with different calculations. The aim of this work is to point out the role of phenomenological optical potentials which have already been used in distorted-wave impulse approximation (DWIA) calculations for spin excitations in this energy domain and the role of different free nucleon-nucleon interactions.

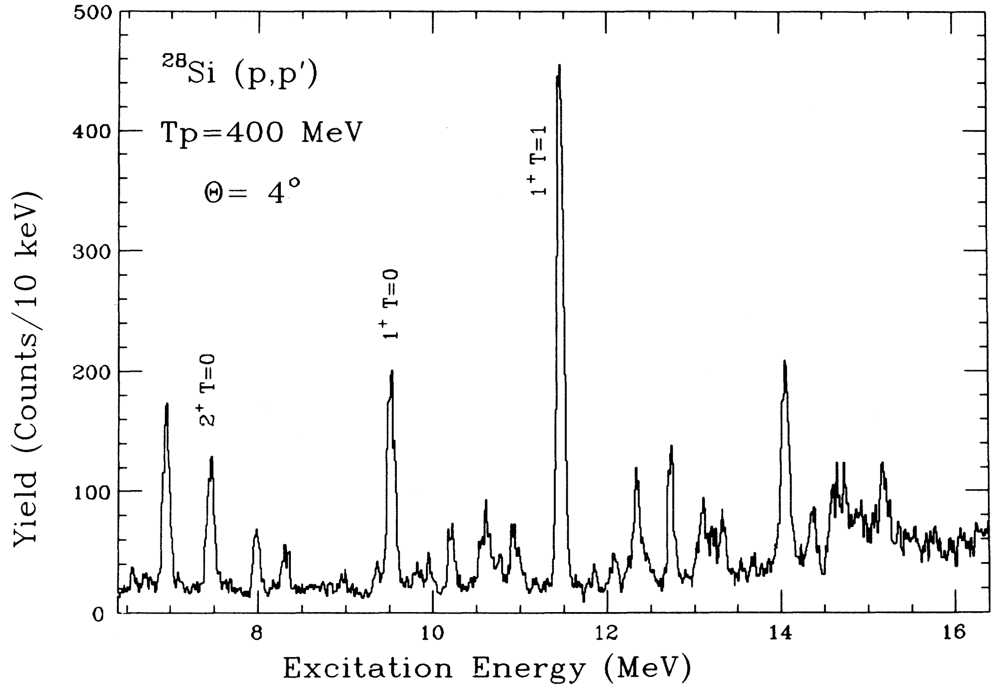


FIG. 1. Inelastic (p,p') spectrum taken at $\Theta=4°$ for a projectile energy $T_p=400$ MeV.

II. EXPERIMENTAL PROCEDURE

The experiment was carried out at the Laboratoire National Saturne (LNS) using the high-resolution spectrometer SPES 1.[14] In the dispersion matching mode, the energy resolution was about 80 keV at 200 MeV where 70 keV came from the straggling in the target; the energy resolution was 100 keV at the other projectile energies, partly due to the target and partly to the detector resolution. The natural silicon target (92.23% abundant in ^{28}Si) was 13.3 mg cm^{-2} thick and homogeneous to better than 3%. The polarization of the beam was periodically measured by an upstream polarimeter using a CH_2 target. The polarization ranged from 92 to 95 %. The angular acceptance of the spectrometer with full efficiency was 2°. In reconstructing the trajectories, the scattering angle was determined to better than 0.1°. For each measurement, the angular acceptance was divided in five bites, each 0.4° wide. For the 1^+ states, measurements were performed from 3° to 9°. A spectrum taken at 4° and $T_p=400$ MeV is given in Fig. 1. Some spectra were also taken at larger angles including the maximum of the angular distributions for the 6^- $T=0$ and 1 states located at 11.58 and 14.35 MeV.[15] At $T_p=600$ MeV, cross sections and analyzing powers were measured for the elastic scattering in order to fit an optical potential parameter set which was not available at this energy (see Fig. 2).

A 2^+ state is known to be located at 9.48 MeV (Ref. 16) and, with the present energy resolution, cannot be separated from the 1^+ $T=0$ state at 9.50 MeV. In order to conduct a multipole analysis of the strength observed in the peak at 9.50 MeV, we have measured in the same

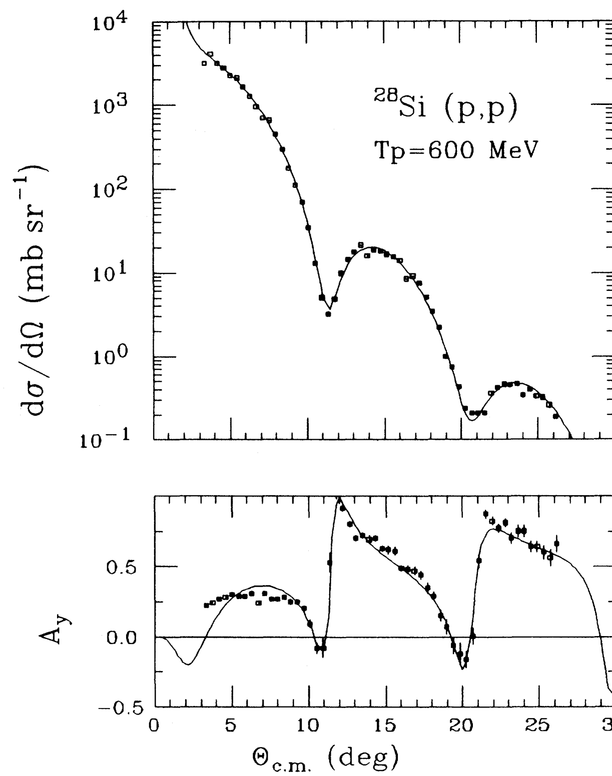


FIG. 2. Differential cross section and analyzing power for ^{28}Si(p,p) at 600 MeV. The full line is the result of the fit with the optical parameters of Table II.

experiment the angular distribution of the differential cross sections and analyzing powers for the sum of two known 2^+ states located at 7.38 and 7.42 MeV (Ref. 16) which cannot be separated in the present experiment.

Measurements were also performed at $T_p = 800$ MeV. However, it was found that, because of the rapid increase of the cross section for the excitation of parity-favored states and the large density of such states around 10 MeV of excitation energy, it was impossible in the present experimental conditions to extract with any confidence cross sections for the 1^+ $T=0$ and $T=1$ states.

Absolute calibrations of the beam monitor were obtained at 200, 400, and 600 MeV by the carbon activation method, which is the standard method used at the LNS. This method has been proven to give reliable absolute cross sections within 10%.[17] At 200 MeV, the absolute cross sections for the 1^+ states obtained by this method are in perfect agreement with previous results measured at Orsay.[2] At 400 MeV, it was found after the experiment that the carbon activation results were unreliable due to a mishandling of the samples. Therefore, at this energy, absolute cross sections were obtained by normalization to the results of Ref. 11 for the 11.45 MeV state and to the results interpolated from Ref. 15 for the 6^- $T=1$ state. The error bars for the deduced cross sections at 400 MeV take into account this uncertainty.

III. THEORETICAL ANALYSIS

In intermediate energy (p,p') scattering, the measured angular distributions of the differential cross sections are compared in shape and magnitude to the calculated ones for each state and an average normalization factor, namely, the ratio of measured to calculated cross sections, is obtained. Since 1^+ states have a forward-peaked angular distribution, the normalization factor R is deduced at small momentum transfer ($0.2 \le q \le 0.8$ fm^{-1}) where the contributions from other multipolarities are generally negligible. The predicted cross sections are calculated by different codes using the distorted wave impulse approximation. Three ingredients are needed to calculate the differential cross sections $d\sigma/d\Omega$ and analyzing powers A_y: (i) the one-body transition density which is obtained from the shell-model wave functions, (ii) the distorted incoming and outgoing waves deduced from the optical potential, and (iii) the nucleon-nucleon (N-N) interaction which induces the transition.

Different shell-model calculations exist for the 1^+ transitions in ^{28}Si (Refs. 18 and 19) which all use the Wildenthal interaction.[20] For all the discussions in this paper, we will use the most recent shell-model calculations of Ref. 19; this model gives the right energies for the strongest $T=0$ and the 1^+ states (9.40 and 11.45 MeV, respectively); however, it strongly underpredicts the strength of the 11.45 MeV level. The shell-model one-body transition density matrix elements (hole-particle) reduced in both J and T space are given for these two states in Table I. For the input to the code DW81, the Raynal phase convention[21] have been used without any normalization.

The N-N interaction in all the calculations has been restricted to the free N-N interaction. We will subsequently study the sensitivity of the calculated cross sections to the choice of both the optical potential and the free N-N interaction.

TABLE I. Shell-model hole-particle configurations for the 1^+ 9.50 MeV $T=0$ state, and the 1^+ 11.45 MeV $T=1$ state in ^{28}Si from Ref. 19. The phase conventions are those of Raynal (Ref. 21). No normalization factor is needed for the input of DW81.

Configuration	9.50 MeV $T=0$	11.45 MeV $T=1$
$1d_{5/2}$ $1d_{5/2}$	-0.0483	-0.2335
$1d_{5/2}$ $1d_{3/2}$	-0.2083	-0.1255
$2s_{1/2}$ $2s_{1/2}$	-0.0071	-0.0929
$2s_{1/2}$ $1d_{3/2}$	$+0.0371$	$+0.1286$
$1d_{3/2}$ $1d_{5/2}$	-0.5563	-0.2409
$1d_{3/2}$ $2s_{1/2}$	$+0.0548$	$+0.1737$
$1d_{3/2}$ $1d_{3/2}$	$+0.0880$	$+0.0361$

A. The optical potential

It has been shown[5,6] that optical potentials obtained in the folding model using either the free t matrix of Franey and Love[7] or the Nakayama-Love G matrix[6] derived from the Bonn potentials[10] give distortion effects differing by as much as 30% for the GT transition in light nuclei. In the present work only phenomenological optical potentials are considered. These potentials have been used by different authors[2,11,22,23] in their analysis of intermediate-energy inelastic proton scattering on ^{28}Si. The elastic cross sections calculated with these potentials differ as much as 20% at forward angles.

To study the distortion effects of different phenomenological optical potentials, calculations were performed at each bombarding energy T_p using the same code and the same N-N interaction: the DWIA code RESEDA with the phase shifts of Arndt *et al.*[8] This method will be described in more detail in Sec. III B. In order to facilitate comparisons with other calculations, the form of the optical potential used is recalled:

$$V(r) = V_{\mathrm{Coul}} + V_R F_R(r) + iW_I F_I(r) - \left[\frac{\hbar}{m_\pi c}\right]^2 [V_{SO} G_{RSO} + iW_{SO} G_{ISO}(r)]\mathbf{L}\cdot\boldsymbol{\sigma} ,$$

where

$$F_k(r) = \left[1 + \exp\left[\frac{r - r_k A^{1/3}}{a_k}\right]\right]^{-1}$$

with $k = R$ or I,

$$G_k(r) = \frac{1}{r}\frac{d}{dr}F_k(r)$$

with $k = RSO$ or ISO.

This potential was used in a Schrödinger equation with relativistic kinematics and with the reduced mass replaced by the reduced total energy in the center-of-mass

TABLE II. Phenomenological Woods-Saxon optical potential parameters for proton elastic scattering on ^{28}Si.

T_p (MeV)	Set	V_R (MeV)	r_R (fm)	a_R (fm)	W_I (MeV)	r_I (fm)	a_I (fm)	Ref.
200	1	−8.50	1.452	0.504	−19.42	1.117	0.605	11
200	2	−10.10	1.45	0.50	−23.09	1.12	0.60	22
200	3	−12.105	1.30	0.72	−16.875	1.00	0.740	23
200	4	−12.401	1.386	0.55	−16.382	1.047	0.753	2
400	1	−13.84	1.029	0.434	−27.18	1.10	0.576	11
400	2	−19.00	1.03	0.43	−37.31	1.10	0.58	22
600		+1.619	1.434	0.325	−18.573	1.277	0.582	
		V_{SO} (MeV)	r_{SO} (fm)	a_{SO} (fm)	W_{SO} (MeV)	r_{ISO} (fm)	a_{ISO} (fm)	Ref.
200	1	−3.483	0.865	0.656	2.878	0.980	0.545	11
200	2	−4.14	0.86	0.66	3.42	0.98	0.55	22
200	3	−2.13	0.94	0.64	3.075	0.957	0.59	23
200	4	−3.01	1.01	0.574	1.725	1.01	0.574	2
400	1	−0.882	0.944	0.475	2.828	0.956	0.592	11
400	2	−1.21	0.94	0.47	3.88	0.96	0.59	22
600		−1.784	1.043	0.664	3.386	1.043	0.664	

frame. The values of V_{SO} and W_{SO} should be multiplied by 4 for the input convention of DW81. Optical parameter sets are given in Table II. At 200 MeV, 4 sets were used: sets 1 and 2 are given, respectively, in Refs. 11 and 22; set 3 is extrapolated to 200 MeV from values given at 80, 100, 134, and 180 MeV.[23] Set 4 has been used in Ref. 2 for ^{28}Si. At $T_p=600$ MeV, the optical parameters were obtained by fitting the elastic differential cross section and A_y measured during the present experiment (see Fig. 2).

The differential cross sections calculated with the different optical potential sets for the 1^+ $\Delta T=1$ and 0 transitions are given in Figs. 3(a) and 3(b) for $T_p=200$ MeV and in Figs. 4(a) and 4(b) for $T_p=400$ MeV. At 200 MeV, differences of 22% are obtained for sets 1 and 4 and 30% for sets 1 and 3, for the $\Delta T=1$ transition. They are 30 and 38 %, respectively, for the $\Delta T=0$ transition in the normalization region. At $T_p=400$ MeV, the differences for the cross sections given by sets 1 and 2 are of the order of 35% for the $\Delta T=1$ transition and 40% for the $\Delta T=0$ transition. Similar results were obtained with the code DW81 and the Franey and Love interaction. When comparing quenchings or normalization factors in different analyses, it is then important to clearly state which optical potential is used and to be aware that the different optical potentials reported in the literature are not equivalent and give different values for the elastic cross sections. At 200 MeV, if one restricts the choice of optical potentials to set 1, which is reported by the authors of Ref. 11 to reproduce reasonably well the elastic scattering, and set 3, which is extrapolated from a systematic study,[23] there are still differences of the order of ±15% in the extracted normalization factors.

The effect of the distortion can also be seen as an attenuation factor in the approximation often used at small momentum transfer ($q \sim 0$):

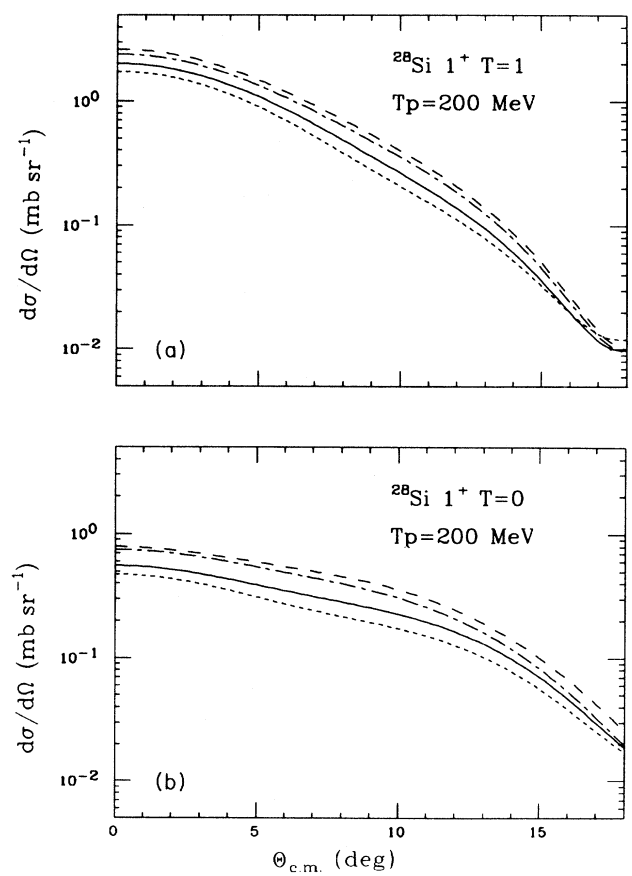
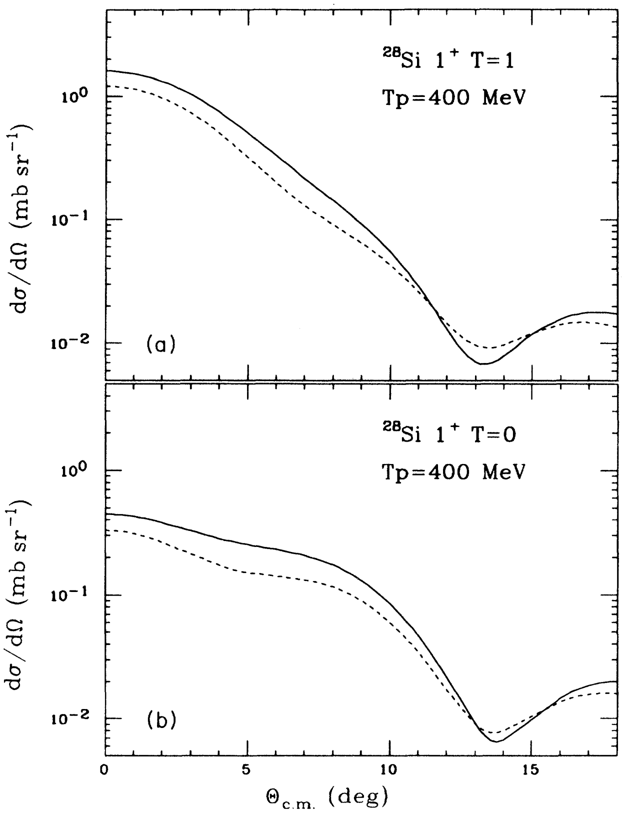


FIG. 3. Cross sections calculated with different optical potential sets at $T_p=200$ MeV. (a) for the 1^+ $T=1$ state at 11.45 MeV. (b) for the 1^+ $T=0$ state at 9.50 MeV. Set 1: full line; set 2: short dashes; set 3: long dashes; set 4: dot dashes.



FIT. 4. Cross sections calculated with optical potential sets 1 and 2 at $T_p=400$ MeV. (a) for the 1^+ $T=1$ state at 11.45 MeV. (b) for the 1^+ $T=0$ state at 9.50 MeV. Set 1: full line; set 2: short dashes.

$$\frac{d\sigma_i}{d\Omega}=CN_iJ_iD_i \ ,$$

where C is a kinematical factor, N_i is the attenuation factor due to the distortion, J_i is the square of the volume integral of the N-N interaction, and D_i is the square of the transition density; the subscript $i=0$ stands for the isoscalar ($T=0$) spin-dependent term and $i=1$ stands for the isovector ($T=1$) spin-dependent term. Calculations performed with the full shell-model wave functions given in Table I or with a simple wave function as $(d_{5/2}^{-1}\text{-}d_{3/2})$ show that the $N_i(q\sim 0)$ values do not depend on the configuration but, on the contrary, they are dependent on the isospin coupling (see Table III). In using the above approximation to extract the energy dependence of the ratio of the volume integrals J_0/J_1 from the measured

TABLE III. Attenuation factors N_1 and N_0 at different T_p energies, for the spin-isovector and -isoscalar transitions at $\Theta=0°$.

T_p (MeV)	Set	N_1	N_0
200	1	0.40	0.29
	3	0.53	0.41
400	1	0.35	0.25
600		0.39	0.30

cross section at small q, an uncertainty of 15% results from the fact that the attenuation factors N_0 and N_1 are different and strongly dependent on the choice of the optical potential.

B. The interaction

All the calculations were performed with the optical potential set 1 at $T_p=200$ and 400 MeV and with the set given in Table II at $T_p=600$ MeV. Two different methods were used for the calculations.

(a) The well-known code DW81, which is an extended version of the program DWBA70 of Schaeffer and Raynal modified by Comfort[21] with the t matrix of Franey and Love deduced from the Arndt *et al.* phase-shifts[8] taken at 210, 425, and 650 MeV. Exchange terms are treated explicitly.

(b) The DWIA code RESEDA (Ref. 24) which directly uses nucleon-nucleon phase shifts following a method proposed by Haybron[25] for the central part of the interaction and extended by Comparat[26] to the complete interaction. Starting directly from the measured N-N phase-shifts, the t matrix in the q space is deduced and is not explicitly separated in central, spin-orbit, spin and tensor terms as in the Franey and Love interaction but all the terms are present anyway. Exchange terms are implicitly included in the N-N amplitudes, so there is no need to separate them in such a type of calculation. With this method, the computation time is reduced by a factor of 40 compared to DW81.

In Ref. 27 the N-N interaction $V(x,x_j)$, which produces the inelastic scattering, was approximated by

$$V(x,x_j)=t(E,q)\delta(\mathbf{r}-\mathbf{r}_j) \ ,$$

where $x\,(x_j)$ stands for the space, spin, and isospin coordinates of the incident (jth target nucleon) and r is the relative coordinate in the nucleon-nucleus center-of-mass system. Such an approximation is not needed, the full calculation can be carried out by performing two Fourier transforms.[26] The term appearing in Eq. (10) of Ref. 27,

$$d_{\lambda\lambda'}^{SS'}(q)\int \chi_{m_b n_b}^{(-)*}(r)\left\langle f\left|\sum_{j=1}^{A}\frac{\delta(r-r_j)}{r_j^2}\mathcal{Y}_{J'}^{M'}(\hat{x}_j)\right|i\right\rangle \chi_{m_a n_a}^{(+)}(r)d\mathbf{r} \ ,$$

becomes

$$\int \chi_{m_b n_b}^{(-)*}(r)\left[\int \left\langle f\left|\sum_{j=1}^{A}\mathcal{Y}_{J'}^{M'}(\hat{x}_j)j_L(q'r_j)\right|i\right\rangle j_L(q'r)d_{\lambda\lambda'}^{SS'}(q')q'^2dq'\right]\chi_{m_a n_a}^{(+)}(r)d\mathbf{r} \ .$$

Since the matrix element $\langle f|\cdots|i\rangle$ decreases rapidly with q', the integral over q' can be calculated by carrying the integration over the limited region of q' where the N-N amplitude $t(E,q')$ is known ($q'_{max}=3.1$ fm^{-1} at 200 MeV and $q'_{max}=5.37$ fm^{-1} at 600 MeV).

Two different sets of phase shifts were used, those of Arndt et al.[8] (A) and those of Bystricky et al.[28] (B) which are fitted on independent nucleon-nucleon scattering experiments. At 200 MeV the phase shifts deduced from the Paris potential[9] and those deduced from the Bonn potential by Machleidt[10](M) were also used.

It was verified that both RESEDA and DW81 predictions for the favored parity 2^+ state at 1.78 MeV in ^{28}Si agree within a few percent. However, since the exchange in the scattering process is treated differently in RESEDA and DW81, larger differences can be expected for transitions with an important contribution from the exchange terms.

In DW81, the exchange terms are treated explicitly: As a result, the effective interaction becomes nonlocal and depends on the individual momenta of the interacting nucleons. For 1^+ excitations, the code RESEDA only allows the normal-parity amplitudes $L=0$ and 2. The code DW81 also allows the same amplitudes but, in addition, the momentum-dependent terms that come from the explicit treatment of the exchange give rise to abnormal-parity amplitudes ($L=1$ in this case). The role of these abnormal-parity amplitudes in the excitations of 1^+ transitions has been studied in some detail in Refs. 29 and 30 for the 1^+ $\Delta T=0$ and 1^+ $\Delta T=1$ excitations in ^{12}C. The abnormal-parity amplitudes, noted [111] in the [LSJ] representation, are very important compared to the normal-parity amplitudes [011] and [211]. Indeed, setting these [111] amplitudes equal to zero drastically changes the (p,p') cross sections for exciting the 1^+ states, especially for the $T=0$ state.

1. The 1^+ $\Delta T=1$ transition

In Figs. 5(a)–5(c) are given the cross sections calculated for the 11.45 MeV level at the three T_p energies with the codes DW81 and RESEDA. At 200 MeV the three sets of phase shifts (A, B, and M) give results which differ by less than 10% in the angular region from 0° to 12°. The curve obtained with the phase shifts deduced from the Paris potential is not drawn in Fig. 5 as it is identical to the curve A within 5%. The cross sections calculated with DW81 also have very similar values below 7°. The analyzing powers are nearly identical for all RESEDA and DW81 calculations below 10°.

At 400 MeV, the shapes of the angular distributions given by RESEDA with the A and B phase shifts are similar, the difference in the absolute cross sections lies between 10 and 20 %; the difference between RESEDA and DW81 cross sections is about the same. At 600 MeV, all RESEDA cross sections differ only by 10% but DW81 cross sections are larger by more than 40%. At small momentum transfer, the analyzing powers, always small and negative, are rather similar for the different calculations.

The large difference between RESEDA and DW81 calculations at 600 MeV, even at $\Theta=0°$, is surprising since the isovector spin interaction is largely dominated by the central $V_{\sigma\tau}$ term and is well determined. This difference is not understood. DW81 calculations performed with the previous Love and Franey[31] and the new Franey and Love[7] interactions give almost identical results at each energy [see Figs. 5(a)–5(c)].

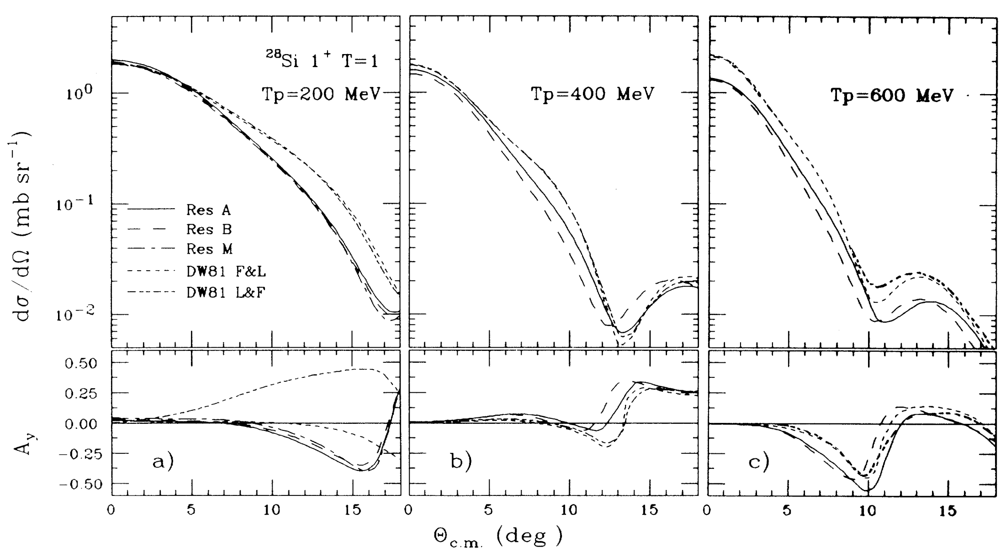


FIG. 5. Cross sections and analyzing powers for the 1^+ $T=1$ state calculated with different codes. The RESEDA results are drawn as a full line for the Arndt et al. phase shifts (Ref. 8), as long dashes for the Bystricky et al. phase shifts (Ref. 28), and as dot dashes for the Machleidt et al. phase shifts (Ref. 10). The DW81 results using the Franey and Love interaction (Ref. 7) are drawn in short dashes and in long and double short dashes for the Love and Franey interaction (Ref. 32). (a) at $T_p=200$ MeV. (b) at $T_p=400$ MeV. (c) at $T_p=600$ MeV.

2. The 1^+ $\Delta T=0$ transition

The angular distributions and analyzing powers are given in Figs. 6(a)–6(c) at the three T_p energies. At 200 MeV, the shape of the angular distributions calculated with the code RESEDA and the three sets of phase shifts are nearly identical, all cross sections agree within 10%. The analyzing powers A_y are also very similar. At 400 MeV, the curves obtained with the phase shifts of Arndt *et al.* and those of Bystricky *et al.* are more different in shape. At 600 MeV, the phase-shift sets A and B again give very similar results.

At 200 MeV, DW81 cross sections are always larger than RESEDA cross sections, the ratio of the DW81 to the RESEDA cross sections increases from 1.4 at 4° to 2.2 at 9°. At 400 and 600 MeV, the cross sections given by RESEDA and DW81 are very similar at 0° but the shapes of the angular distributions differ between 0° and 7°, DW81 cross sections always being larger than RESEDA cross sections.

At small momentum transfer, the isoscalar spin interaction is about three times weaker than the central isovector spin interaction $V_{\sigma\tau}$ and has nearly equal contributions from central and tensor terms. Its determination from the N-N phase shifts is less straightforward than for the central $V_{\sigma\tau}$ term. This is illustrated by comparing DW81 calculations performed with the previous Love and Franey[31] and the new Franey and Love interactions.[7] Both calculations give similar results at 400 MeV but differ significantly at 200 and 600 MeV.

For the $\Delta S=1$, $\Delta T=0$ interaction, the results obtained with RESEDA and with DW81 differ strongly in absolute value and in shape at 200 MeV; it is also at this energy that the DW81 calculations done with the previous Love and Franey interaction differ significantly over the whole angular range considered.

IV. COMPARISON BETWEEN THE EXPERIMENTAL RESULTS AND THE CALCULATIONS

In order to compare the results obtained at different energies, the differential cross sections and analyzing powers are plotted as a function of the momentum transfer q. The experimental results will be compared with calculations performed with the code DW81 using the Franey and Love t matrix and with the code RESEDA using only the Arndt phase shifts since the sets of phase shifts of Refs. 8 and 28 give results which differ by less than 10%.

A. The 1^+ $T=1$ state at 11.45 MeV

The theoretical cross sections are compared to the experimental data for the $T=1$ state in Figs. 7(a)–7(c). The shapes of the angular distributions are correctly reproduced by both RESEDA and DW81 calculations.

At each energy, and for the two types of calculations, the normalization factor R of the theoretical curves is obtained by a least-squares-fit method. The factors R are given in Table IV; the upper errors are due to the fit. At 600 MeV, the lack of data points at small momentum transfer gives more uncertainty on the fit.

The lower errors include the uncertainties coming from the absolute cross sections and from the distortion due to the different optical potentials. The latter uncertainty is mainly responsible for the large value of these errors. At 200 and 400 MeV, the R factors given by RESEDA and by DW81 are close, at 600 MeV they are not compatible within the errors. The R factors deduced from DW81 calculations remain constant with increasing energy. The R factors extracted from RESEDA seem to increase slightly with T_p, however, due to the large uncertainties, such an

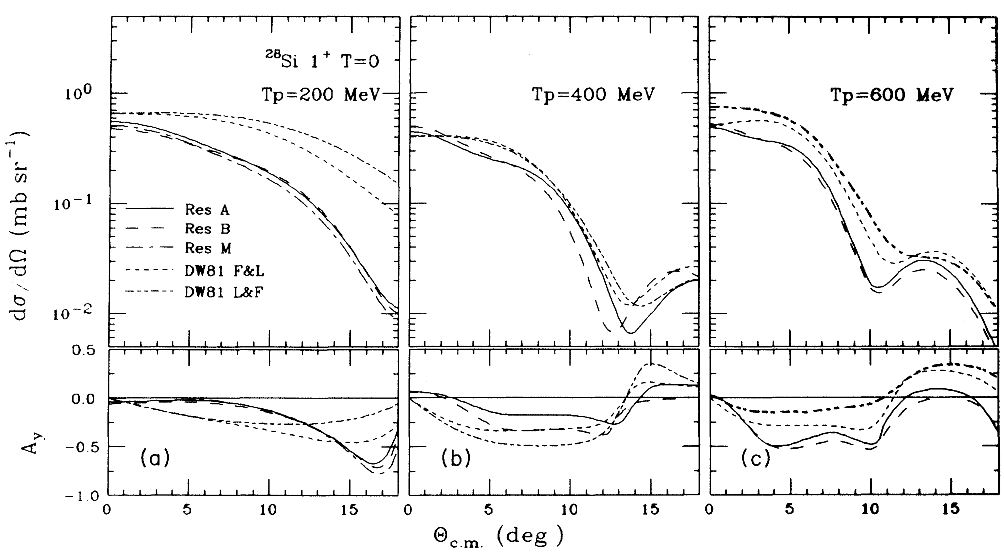


FIG. 6. Same as Fig. 5, but for the 1^+ $T=0$ state.

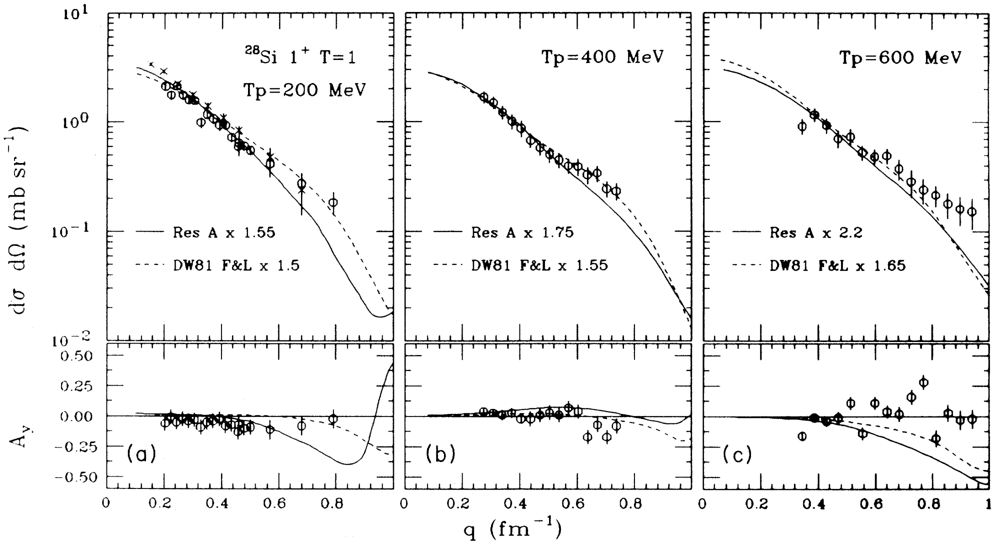


FIG. 7. Comparison between experimental results and predictions for the 1^+ $T=1$ state. The full line is the result obtained by RESEDA with the Arndt phase shifts. The short-dashed curve is the result of DW81. (a) at $T_p=200$ MeV. (b) at $T_p=400$ MeV. (c) at $T_p=600$ MeV. The crosses represent the Orsay data of Ref. 2. The open circles are the present data.

energy dependence cannot be ascertained. In Fig. 7 the measured A_y values are also compared with the predicted ones; at 200 MeV they are slightly negative.

B. The 1^+ $T=0$ state at 9.50 MeV

The observed peak at 9.5 MeV is the sum of a 1^+ $T=0$ state at 9.50 MeV and a 2^+ state at 9.48 MeV. In the multipole analysis of the data, it is assumed that the shape of the angular distribution of the 2^+ state at 9.48 MeV is identical to that of the sum of the 2^+ states at 7.38 and 7.42 MeV which has been measured in the present experiment. It has been verified that this angular distribution is similar in shape to the one calculated for the low-energy 2^+ state given by the model of Brown and Wildenthal[19] and measured experimentally at 200 MeV.[32]

The experimental angular distribution is then fitted by

$$(d\sigma/d\Omega)_{\exp}=R\,(d\sigma/d\Omega)^{1^+}+\lambda(d\sigma/d\Omega)^{2^+}\ .$$

Once the parameters R and λ are determined, the analyzing power A_y is calculated by

$$(A_y)_{\rm calc}=\frac{R\,(d\sigma/d\Omega)^{1^+}A_y^{1^+}+\lambda(d\sigma/d\Omega)^{2^+}A_y^{2^+}}{(d\sigma/d\Omega)_{\exp}}\ .$$

At each incident energy, the values of $(d\sigma/d\Omega)^{1^+}$ and $A_y^{1^+}$ used in this fit are the theoretical ones, calculated with RESEDA or DW81. The λ value is assumed to be the same for both fits. The 2^+ cross section is assumed to vary with energy as the measured cross section of the 2^+ states at 7.4 MeV.

The 1^+ $T=0$ and 2^+ cross sections and the fit obtained are given for the three incident energies in Figs. 8–10 with the R values needed for the fits. For the A_y values, the agreement is good at 400 and 600 MeV; at 200 MeV, the predicted A_y are not negative enough for the RESEDA calculations.

In Table IV are given the normalization factors R at the three energies. For the 1^+ $T=0$ state in ^{28}Si, the R value from the RESEDA calculations appear to increase

TABLE IV. Ratio R of experimental to predicted cross sections for the 1^+ $T=1$ and 1^+ $T=0$ states. The calculations are performed with RESEDA and DW81. Two errors are given for each R value: the upper one is the uncertainty on the fit at a given energy, the lower one accounts for the uncertainty on the optical potential and on the absolute normalization of the experimental data. For the 1^+ $T=0$ state, errors due to the 2^+ level subtraction are included in both errors (see text).

T_p	R ($T=1$)		R ($T=0$)		R ($T=1$)/R ($T=0$)	
(MeV)	RESEDA	DW81	RESEDA	DW81	RESEDA	DW81
200	$1.55^{0.10}_{0.25}$	$1.50^{0.10}_{0.25}$	$1.00^{0.10}_{0.15}$	$0.70^{0.06}_{0.10}$	1.55 ± 0.20	2.14 ± 0.25
400	$1.75^{0.10}_{0.30}$	$1.55^{0.10}_{0.25}$	$1.30^{0.15}_{0.25}$	$1.10^{0.13}_{0.20}$	1.35 ± 0.20	1.41 ± 0.20
600	$2.20^{0.20}_{0.35}$	$1.65^{0.20}_{0.30}$	$1.55^{0.25}_{0.30}$	$1.10^{0.20}_{0.25}$	1.42 ± 0.25	1.50 ± 0.30

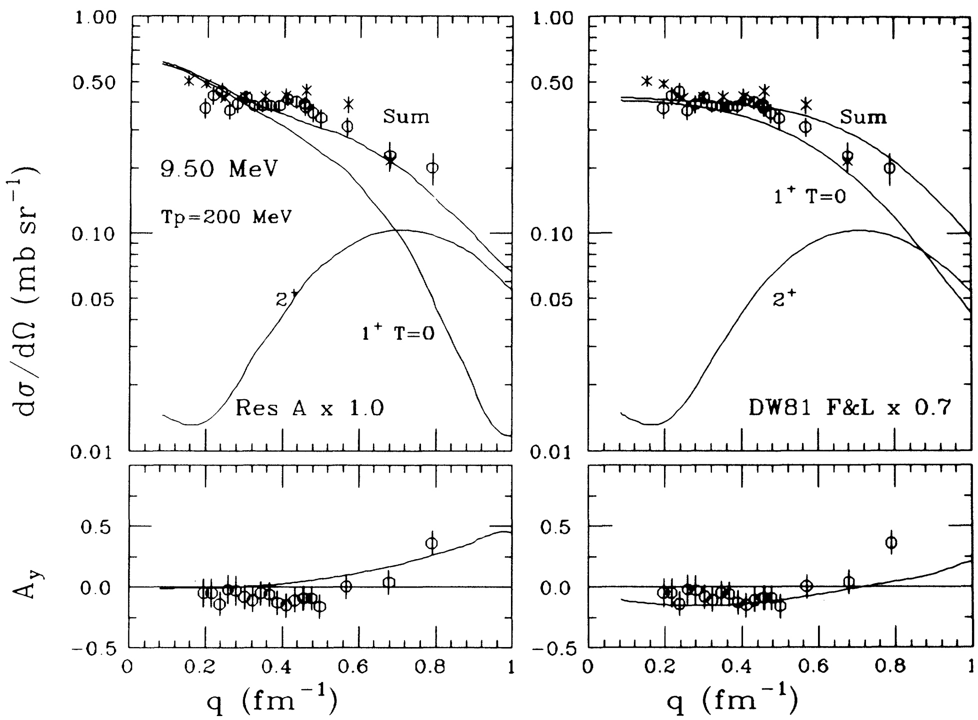


FIG. 8. Comparison between experimental results and predictions given by RESEDA and DW81 for the 9.5 MeV states (see text) at $T_p = 200$ MeV. The crosses represent the Orsay data of Ref. 2. The open circles are the present data.

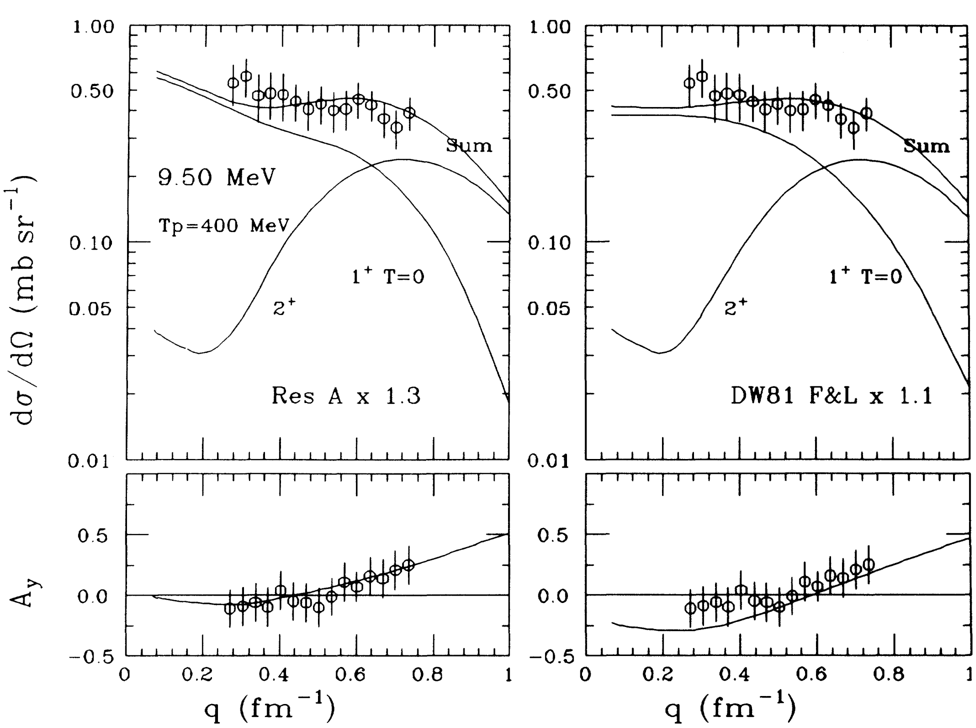


FIG. 9. Same as Fig. 8 but at $T_p = 400$ MeV.

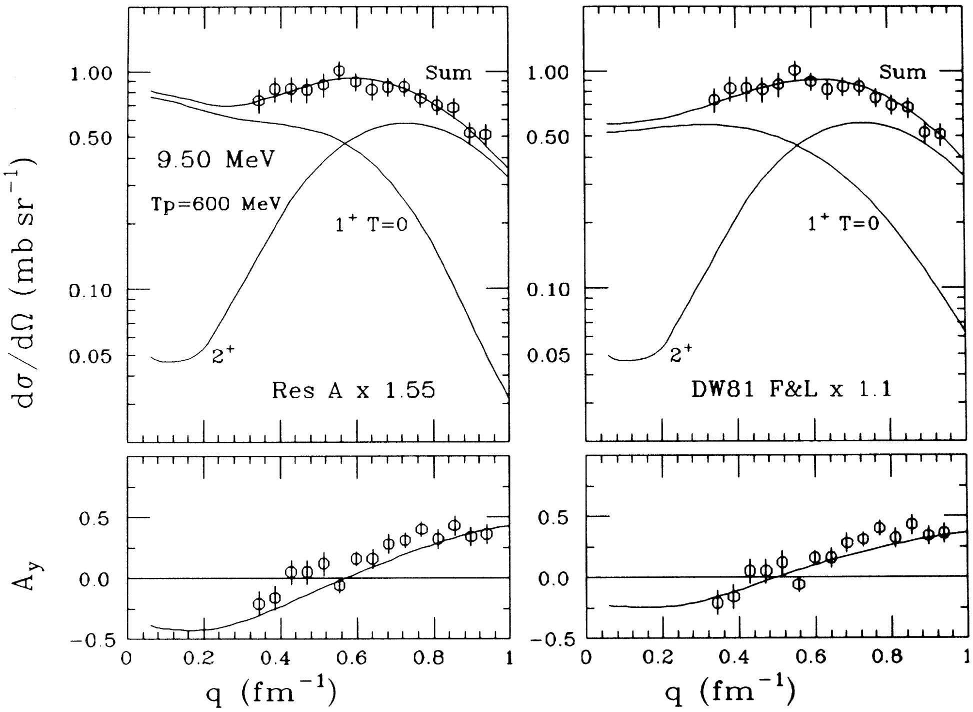


FIG. 10. Same as Fig. 8 but at $T_p = 600$ MeV.

smoothly with energy. Due to the large total uncertainty on R, an energy dependence of the isoscalar spin interaction cannot be firmly established. As a difference with the 1^+ $T=1$ state, the factors R given by RESEDA or DW81 do not agree within the fitting errors at 200 MeV. The R value given by DW81 increases rapidly between 200 and 400 MeV. Such an increase was already observed in Ref. 11, where it is also pointed out that, for the well known 1^+ $T=0$ state at 12.7 MeV in ^{12}C, DW81 calculations with the Franey and Love interaction overpredict the cross sections at 200 MeV but agree with the experimental values at 400 MeV. In order to understand this trend, DW81 and RESEDA calculations for the 1^+ $T=0$ state in ^{12}C were performed and compared to the data points of Comfort[30] at 200 MeV and Jones[33] at 398 MeV. The RESEDA calculations reproduce the data at both energies without any normalization factor. The DW81 calculations at 200 MeV overpredict the data as pointed out in Ref. 11.

For proton energies of 150 and 200 MeV, the agreement with the experimental measurements is much better, at least for small scattering angles, if the abnormal-parity amplitude [111] is set equal to zero in DW81.[29,30] If the better agreement of the experimental results with RESEDA calculations or with the DW81 calculations, where the [111] abnormal-parity amplitude is set to zero is not a coincidence, it would suggest the following: either the wave function for the 1^+ states in ^{12}C is unsatisfactory, or the exchange term involving the [111] amplitude derived with the Franey and Love interaction in the $\Delta S=1$, $\Delta T=0$ channel is overestimated in DW81 at 200 MeV.

For the 1^+ $\Delta T=0$ transition in ^{28}Si, the weight of the

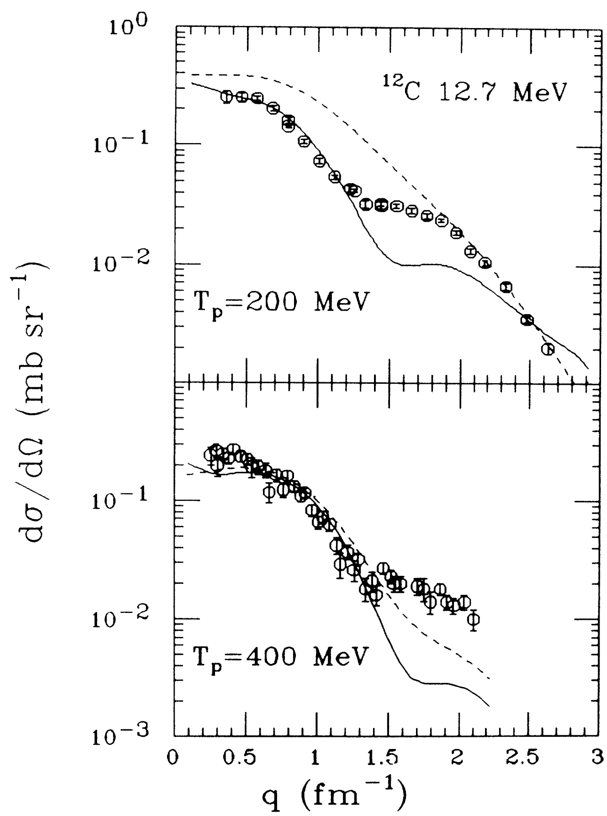


FIG. 11. Cross sections for the 12.7 MeV 1^+ $T=0$ state in ^{12}C. The RESEDA calculations are drawn as a full line and the DW81 calculations as a dashed line. The normalization factor is 1 for both calculations. The experimental data are from Ref. 30 at 200 MeV and from Ref. 31 at 400 MeV.

abnormal-parity amplitude [111] in an $[LSJ]$ representation is smaller compared to the [011] and [211] amplitudes than for the 1^+ $\Delta T=0$ transition in ^{12}C; it can hardly explain the difference between the RESEDA and the DW81 results. At 400 MeV, RESEDA and DW81 results agree within 10% (see Fig. 11).

V. SUMMARY AND DISCUSSION

Some general conclusions can be drawn from the results presented in this paper. The attenuation due to the distortion is extremely sensitive to the optical potential used; this may explain differences obtained for the quenching of isovector spin-flip and Gamow-Teller transitions extracted from different experiments, where different phenomenological optical potential parameters were used. Moreover, the attenuation factors given by the same optical potential for spin-isovector and spin-isoscalar transitions are different.

Two DWIA methods are used for the calculations: RESEDA, which directly uses the nucleon-nucleon phase shifts, and the DW81 code which uses the parametrization of the free t matrix of Franey and Love derived from the Arndt phase shifts. The RESEDA calculations, performed with different nucleon-nucleon phase shifts, give very close 1^+ $T=1$ cross sections as expected for a transition induced by the strong and well-known isovector spin interaction. Surprisingly, the different N-N phase shifts lead to the same isoscalar spin interaction which is weak and not considered as well known. For the 1^+ $\Delta T=1$ transition, the results given by the two methods are compatible for small values of the momentum transfer, except at 600 MeV. The normalization factors R obtained with RESEDA appear to increase slightly as a function of the projectile energy for both the isoscalar and the isovector spin-flip transitions; however, due to the large uncertainties introduced by the optical potentials, they are not incompatible with a constant value. The $R(T=0)$ or $R(T=1)$ values obtained with DW81 do not depend on the projectile energy if the $R(T=0)$ value at 200 MeV is discarded. By taking at each angle and for each calculation the ratio $R(T=1)/R(T=0)$ (see Table IV), one gets rid of the uncertainty on the absolute cross sections and most of the uncertainty coming from the choice of the optical potential. Within the errors bars, the RESEDA and DW81 ratios agree except at 200 MeV. It is most likely that, at 200 MeV, the origin of the problem for the 1^+ $T=0$ state lies with some feature of the effective isoscalar spin interaction, where the tensor part is important.

Within the large uncertainties, $R(T=0)$ and $R(T=1)$ values can be considered as independent of the bombarding energy. This implies that, for ^{28}Si and up to 600 MeV, both the isovector and isoscalar spin interactions can be described using the free N-N interaction. It would be interesting to see if density-dependent calculations confirm this result for the isoscalar transition.

The authors acknowledge the assistance of the staff of the LNS and of the Département de Physique Nucléaire–Moyenne Energie (DPHN-ME) during the whole experiment.

---

*On leave from University of Minnesota, Minneapolis, Minnesota 55455.

†On leave from Kyoto University, Japan.

[1]Proceedings of the Workshop on Isovector Excitations in Nuclei [Can. J. Phys. **65**, 635–691 (1987)].

[2]G. M. Crawley, C. Djalali, N. Marty, M. Morlet, A. Willis, N. Anantaraman, B. A. Brown, and A. Galonsky, Phys. Rev. C **39**, 311 (1989).

[3]T. N. Taddeucci, C. A. Goulding, T. A. Carey, R. C. Byrd, C. D. Goodman, C. Gaarde, J. Larsen, D. Horen, J. Rapaport, and E. Sugarbaker, Nucl. Phys. **A469**, 125 (1987).

[4]W. P. Alford, R. Helmer, R. Abegg, A. Celler, D. Frekers, O. Häusser, R. Henderson, K. Hicks, K. P. Jackson, R. Jeppesen, C. A. Miller, and M. Vetterli, Phys. Rev. C **39**, 1189 (1989).

[5]W. G. Love, K. Nakayama, and M. A. Franey, Phys. Rev. Lett. **59**, 1401 (1987).

[6]K. Nakayama and W. G. Love, Phys. Rev. C **38**, 51 (1988); W. G. Love, private communication.

[7]M. A. Franey and W. G. Love, Phys. Rev. C. **31**, 488 (1985).

[8]R. A. Arndt, L. D. Roper, R. A. Bryan, R. B. Clark, B. J. VerWest, and P. Signell, Phys. Rev. D **28**, 97 (1983).

[9]M. Lacombe, B. Loiseau, J. M. Richard, R. Vinh Mau, J. Côté, P. Pirès, and R. de Toureil, Phys. Rev. C **21**, 861 (1979).

[10]R. Machleidt, K. Holinde, and Ch. Elster, Phys. Rep. **149**, 2 (1987).

[11]O. Häusser, R. Sawafta, R. G. Jeppesen, R. Abegg, W. P. Alford, R. L. Helmer, R. Henderson, K. Hicks, K. P. Jackson, J. Lisantti, C. A. Miller, M. C. Vetterli, and S. Yen, Phys. Rev. C **37**, 1119 (1988).

[12]H. Toki, G. F. Bertsch, and D. Cha, Phys. Rev. C **28**, 1398 (1983).

[13]W. G. Love and M. A. Franey, J. Phys. (Paris) Colloq. **45**, C4-231 (1984).

[14]R. Beurtey (unpublished); J. Saudinos, J. C. Duchazeaubeneix, C. Laspalles, and R. Chaminade, Nucl. Instrum. Methods **11**, 77 (1973).

[15]N. M. Hintz, M. A. Franey, M. M. Gazzaly, D. Cook, G. S. Kyle, D. Dehnhard, S. J. Seestrom-Morris, G. W. Hoffmann, M. Barlett, G. S. Blanpied, J. A. McGill, J. B. McClelland, R. L. Boudrie, F. Irom, and G. Pauletta, Phys. Rev. C **30**, 1976 (1984).

[16]P. M. Endt and C. Van der Leun, Nucl. Phys. **A310**, 1 (1978).

[17]H. Quechon, Ph.D. thesis, Université Paris XI, Orsay, 1980.

[18]W. Chung, Ph.D. thesis, Michigan State University 1976.

[19]B. A. Brown and B. H. Wildenthal, Nucl. Phys. **A474**, 290 (1987); B. A. Brown, private communication.

[20]B. H. Wildenthal, in *Progress in Particle and Nuclear Physics,* edited by D. H. Wilkinson (Pergamon, Oxford, 1984), Vol. 11, p. 5.

[21]R. Schaeffer and J. Raynal Program DWBA70 (unpublished); J. R. Comfort extended version DW81 (unpublished).

[22] R. Sawafta, Ph.D. thesis, University of Alberta, 1987.
[23] C. Olmer, A. D. Bacher, G. T. Emery, W. T. Jones, D. W. Miller, H. Nann, P. Schwandt, S. Yen, T. E. Drake, and R. J. Sobie, Phys. Rev. C **29**, 361 (1984).
[24] A. Willis, Ph.D. thesis, Université Paris XI, Orsay, 1968.
[25] R. M. Haybron, Phys. Rev. **160**, 756 (1967).
[26] V. Comparat, Ph.D. thesis, Université Paris XI, Orsay, 1970.
[27] R. M. Haybron and H. McManus, Phys. Rev. **136**, 1730 (1964).
[28] J. Bystricky, C. Lechanoine-Leluc, and F. Lehar, J. Phys. (Paris) **48**, 199 (1987).
[29] W. G. Love and J. R. Comfort, Phys. Rev. C **29**, 2135 (1984).
[30] J. R. Comfort, G. L. Moake, C. C. Foster, P. Schwandt, and W. G. Love, Phys. Rev. C **26**, 1800 (1982); private communication.
[31] W. G. Love and M. A. Franey, Phys. Rev. C **24**, 1073 (1981).
[32] K. H. Hicks, R. G. Jeppesen, C. C. K. Lin, R. Abegg, K. P. Jackson, O. Hausser, J. Lisantti, C. A. Miller, E. Rost, R. Sawafta, M. C. Vetterli, and S. Yen, Phys. Rev. C **38**, 229 (1988).
[33] K. W. Jones, Ph.D. thesis, Rutgers University, 1984 (Los Alamos National Laboratory Report No. LA-10064-T).