Alpha-Particle Scattering from ^{28}Si at 21 to 28 MeV*

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60-point angular distributions for the scattering of α particles to the first four states in ^{28}Si (0^+, 2^+, 4^+, 0^+) were measured from 21 to 28 MeV in 125-keV steps. Fluctuations with full width at half maximum of less than 300 keV were observed in all four channels. Compound-nuclear contributions to energy-averaged data have been estimated (20% to the 2^+ state, 30% to the 4^+ and $0^+_{4.97}$ states) at 25.2, 26.2, and 27.2 MeV. Optical-model fits to the elastic scattering and coupled-channel fits to the 0^+, 2^+, 4^+ states give slightly better agreement with an angular-momentum-dependent absorption. The coupled-channel calculations give an over-all poor reproduction of the data and it is not possible to extract a hexadecapole deformation for ^{28}Si. The extracted value of the quadrupole deformation parameter is $\beta_2 = -0.26 \pm 0.08$ while an upper limit can be placed on the hexadecapole deformation parameter $|\beta_4| \leq 0.1$.

I. INTRODUCTION

The scattering of 104-MeV α particles by ^{20}Ne has clearly demonstrated the presence of a hexadecapole deformation for ^{20}Ne.[1] However, α-particle scattering performed at an incident energy of 16.8 MeV does not indicate any need for a hexadecapole deformation to explain the inelastic scattering.[2] While this result is surprising, it is possible that compound-nuclear effects present in the lower-energy scattering make the inelastic scattering insensitive to the presence of a hexadecapole deformation. This difference in the scattering to the ^{20}Ne 4^+ state can be contrasted with the scattering to the 2^+ state, where compound effects are less, and from which it is possible to get agreement for the quadrupole deformation for both the high- and low-energy α-particle scattering.[1,2]

The present measurements on ^{28}Si were undertaken to further investigate the feasibility of extracting hexadecapole deformations at α-particle energies in the range 21–28 MeV. Limited measurements on ^{28}Si have been reported in this energy region by Bingham[3] for the α_0, α_1, α_{2+3}, α_4, and α_{5+6} groups at 21.6, 23.3, 25.1, and 27.0 MeV over the whole angular range, Kokame *et al.*[4] for the α_0 and α_1 groups at 28 MeV from 15 to 90°, Zelenskaya *et al.*[5] for the α_0 and α_1 groups at 100.5° from 21 to 25 MeV, Chyla *et al.*[6] for the α_0, α_1, and α_2 groups at 26.5 MeV from 20 to 177.5°, and Bobrowska *et al.*[7] for the α_0 group at 27.5 MeV from 20 to 179°. These previous measurements do not constitute a complete enough set of data to be able to determine the importance of compound contributions to the scattering.

In the present work, complete angular distributions have been measured in the energy range from 21 to 28 MeV in 125-keV steps. Fluctuations in the measured excitation functions indicate the presence of a significant compound-nuclear contribution in the data. The elastic scattering data have been analyzed at $E_\alpha = 25.2$, 26.2, and 27.2 MeV in terms of the optical model plus a Hauser-Feshbach contribution. The direct and compound contributions to the scattering were added incoherently. With the compound-nucleus parameters determined from the elastic scattering analysis, the compound contribution to the 2^+ and 4^+ states was calculated and subtracted from the data. The direct part of the elastic and inelastic data was then analyzed in the coupled-channels formalism to extract the quadrupole and hexadecapole deformation of ^{28}Si.

II. EXPERIMENTAL METHOD

The Florida State University super FN tandem Van de Graaff was used to produce a beam of 21- to 28-MeV α particles. The target was made by breaking a bubble blown from a quartz tube (SiO_2) and was 100 keV thick to 24-MeV α particles. 60-point angular distributions were measured using 15 Si surface-barrier detectors mounted in a ring at 10° intervals from 30 to 170° in the lab. The over-all energy resolution was about 200 keV.

Relative solid angles, which were kept small at forward angles and large at backward angles, were obtained by measuring the α-particle yield from a gold target at 9 MeV, where Au(α, α) obeys Rutherford scattering over the whole angular range. Cross sections were obtained by normalizing the Si(α, α) yield to the yield from a thin film of gold on the SiO_2 target at angles forward of 60°, where Au(α, α) obeys Rutherford scattering up to 28 MeV to within ±10%.[8,9] The departure of the Au(α, α) scattering from Coulomb scattering was accounted for by using known optical potentials.[8] The ratio of gold- to quartz-target thicknesses was obtained by measuring the forward angle scattering at 6 MeV,

where both Si(α, α) and Au(α, α) obey Rutherford scattering. The uncertainty in this ratio, and hence in the absolute normalization, is about ±3%. The dead time of the 4096-channel analyzer was less than 10%, and corrections were made for this. The yields from the excited states of ^{28}Si were corrected for the isotopic abundance of ^{28}Si (92.2%). As a consistency check the extracted ^{16}O(α, α)^{16}O cross sections were compared to the cross sections of Bergman and Hobbie[10] and these agree to better than ±10%.

Excitation functions at eight of the sixty angles measured are shown for the α_0 through α_3 groups in Figs. 1–4, respectively. The relative errors shown are a combination of the statistical error, peak fitting error where applicable, and over-all repeatability where data were repeated. In those cases where the carbon and oxygen peaks overlapped with the α_1 through α_3 peaks or when the α_2 and α_3 peaks overlapped, the yields were extracted by fitting the data assuming Gaussian-peak shapes. The peak-fitting error[11] simply involved multiplying the statistical error $\sqrt{T+B}/(T-B)$ by $\sqrt{\chi^2}$ when $\chi^2 > 1$. Here T is the total yield, B is the background yield, and χ^2 is the normalized goodness of fit criterion to Gaussian fits of the overlapping peaks. Also included in the relative errors are the errors in the solid-angle measurements since the cross sections were normalized to an average of several forward-angle gold yields. The resulting errors range from ±2 to ±10% for the ground-state 0^+ cross section, ±3 to ±15% for the 2^+ and 4^+ cross sections, and ±5 to ±50% for the first excited state 0^+ cross sections. The larger errors occur at angular distribution minima and also from peak fitting where applicable.

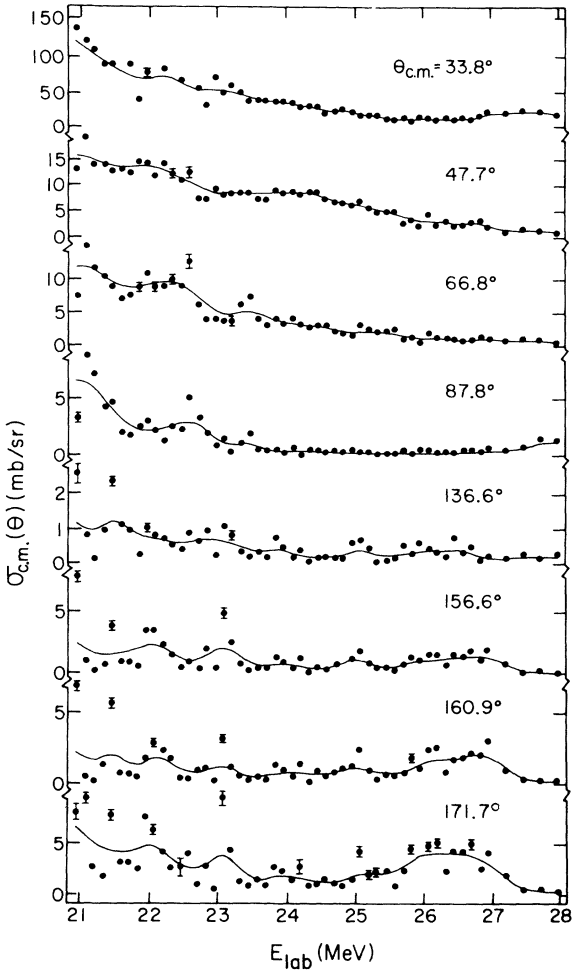

FIG. 1. Selected excitation functions for the ^{28}Si(α, α_0)-^{28}Si reaction with a Gaussian energy average of 500 keV FWHM (solid line).

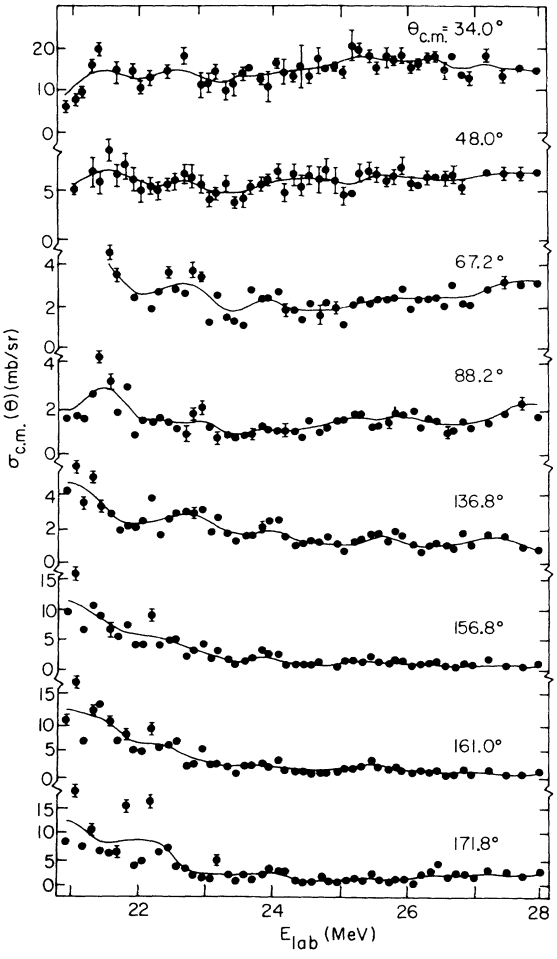

FIG. 2. Selected excitation functions for the ^{28}Si(α, α_1)-^{28}Si$^*_{1.78}$ reaction with a Gaussian energy average of 500 keV FWHM (solid line).

III. ANALYSIS AND RESULTS

The presence of fluctuations with full width at half maximum (FWHM) of less than 300 keV in Figs. 1–4 is clearly visible over the entire energy range, in particular below 24 MeV. This structure appears to be uncorrelated as a function of angle or in the four reaction channels studied here, as can be seen from the angle-integrated cross sections shown in Fig. 5. Similar pronounced structure in $\alpha + ^{28}$Si excitation functions has been seen at lower bombarding energies by Weiss[12] and Lega and Macq.[13] In view of the large negative (α, n) Q value (−8.144 MeV), compound-nuclear processes might still be expected to be evident in this energy range, and therefore, such structure might be expected.

The solid curves in Figs. 1–4 are energy averages with a Gaussian weighting function of 500 keV FWHM. Such an energy increment was felt to be adequate since coherence widths in this mass and energy region are typically less than 100 keV.[14] Measured angular distributions at 25.2, 26.2, and 27.2 MeV for the $0^+, 2^+, 4^+, 0^+$ groups with the above energy average are presented in Figs. 6–8. A compound nuclear (CN) contribution to the energy-averaged data was determined at these three energies from Hauser-Feshback (HF) theory[15] with the simplification given by Eberhard *et al.*,[16] where the sum over all exit channels into which the compound nucleus can decay is replaced by an explicit expression obtained from the Fermi-gas model. In this approximation, Eq. (19) of Ref. 16, the parameters appearing in the sum over the exit channels are the density of spin zero states in the compound nucleus

$$\rho = \frac{2\pi}{W_{cc'}} \frac{\Gamma_0}{D_0} \tag{1}$$

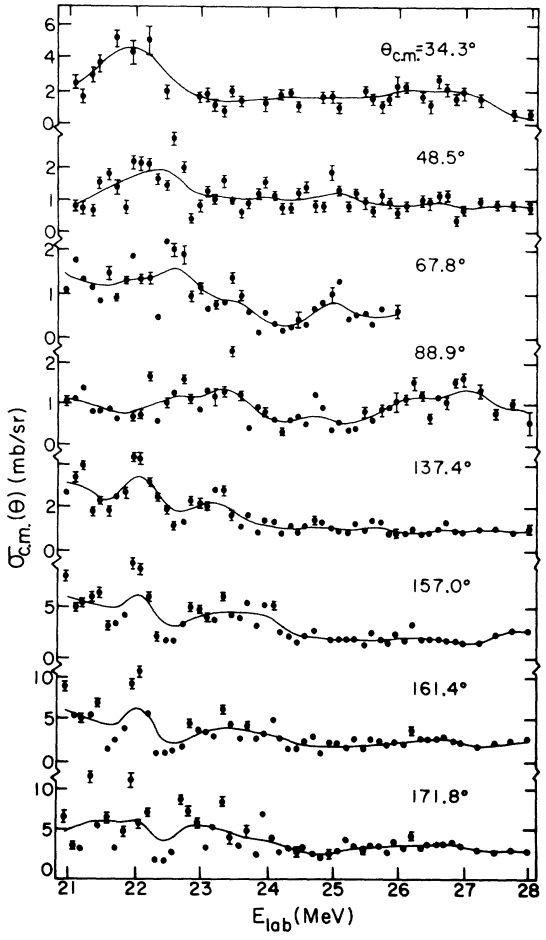

FIG. 3. Selected excitation functions for the ^{28}Si(α, α_2)-^{28}Si$^*_{4.61}$ reaction with a Gaussian energy average of 500 keV FWHM (solid line).

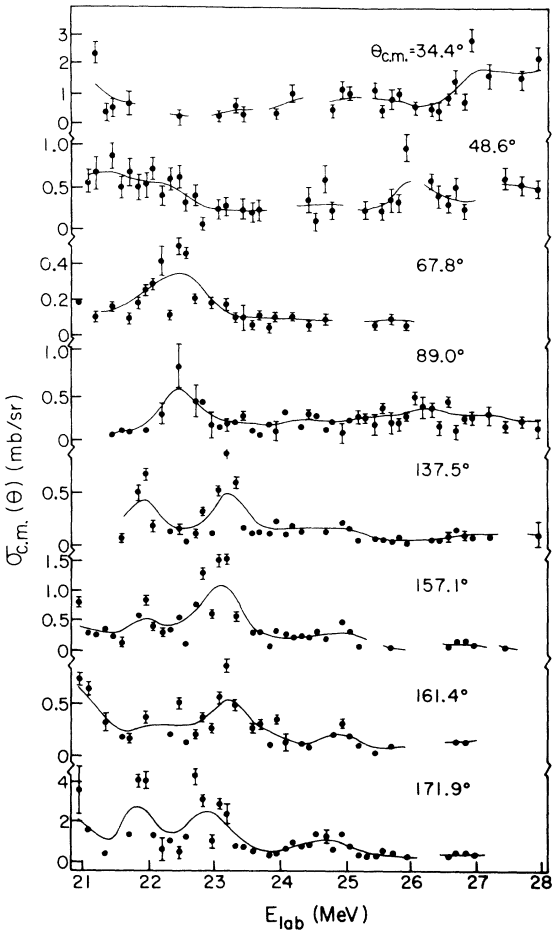

FIG. 4. Selected excitation functions for the ^{28}Si(α, α_3)-^{28}Si$^*_{4.97}$ reaction with a Gaussian energy average of 500 keV FWHM (solid line).

and an average value of the spin distribution parameter (σ) for the various residual nuclei reached by the decay of the compound nucleus. Here $W_{cc'}$ is the width-fluctuation factor. The compound nucleus was assumed to decay predominantly by neutron, proton, and α emission.

Assuming an incoherent addition of direct and compound contributions to the cross sections, the direct part of the elastic data was analyzed with the optical model using the computer code JIB[17] at 25.2, 26.2, and 27.2 MeV. A Woods-Saxon form factor for the nuclear part of the potential $V(r)$ was used where

$$V(r) = V_C(r) - (U + iW) f(r) . \tag{2}$$

Here the Coulomb potential $V_C(r)$ was taken to be that of a uniformly charged sphere and

$$f(r) = \frac{1}{1+\exp[(r-R)/a]} , \quad R = r_0(A_1^{1/3} + A_2^{1/3}) . \tag{3}$$

From angular-momentum-conservation requirements, one might expect the strength of the imaginary potential to be l-dependent.[18] l-dependence scattering from ^{40}Ca (Refs. 19 and 20) and ^{20}Ne (Ref. 2). For ^{28}Si the inclusion of l dependence might also be appropriate since the (α, n) Q value is −8.144 MeV. With a Woods-Saxon form factor[19] absorption becomes

$$W \rightarrow \frac{W}{1+\exp[(l-l_c)/\Delta l]} . \tag{4}$$

The angular momentum cutoff parameter l_c and the diffuseness Δl in the cutoff are average values representing all open exit channels except the elastic one. Although these quantities are related to empirical expressions,[21] they are treated as free parameters in the present calculation along with the parameters describing the direct and compound contributions.

Initially coarse grids for the 25.2-MeV elastic data of U vs W were made for $r_{0R} = 1.0$ to 1.8 fm, $r_{0I} = 1.0$ to 1.8 fm, $a_R = 0.25$ to 0.85 fm, and $a_I = 0.25$ to 0.85 fm, where $R = r_0(A_1^{1/2} + A_2^{1/3})$. In this preliminary analysis volume absorption was assumed and no compound nuclear contribution was included. The results indicated the presence of local minima in the χ^2 surface spaced about every

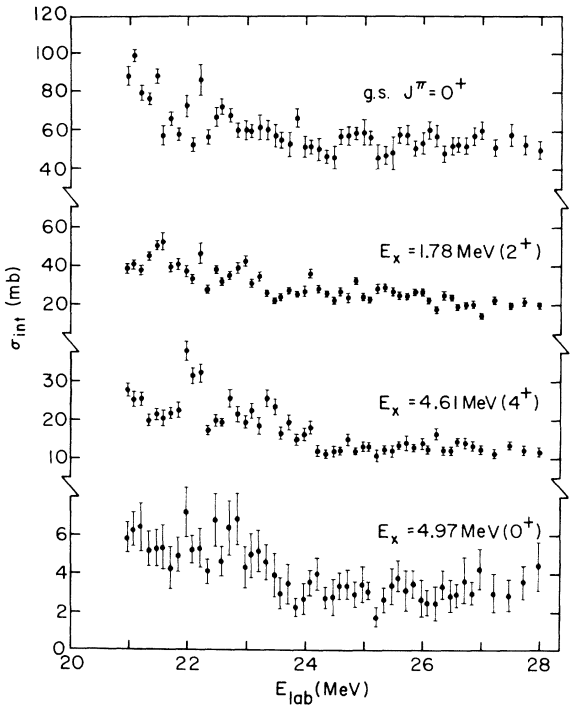

FIG. 5. Angle-integrated excitation functions for the first four α-particle groups from ^{28}Si:

$$\sigma_{int.} = 4\pi \left(\frac{\sum_i \sigma(\theta_i) \sin\theta_i \Delta\theta_i}{\sum_i \sin\theta_i \Delta\theta_i} \right) .$$

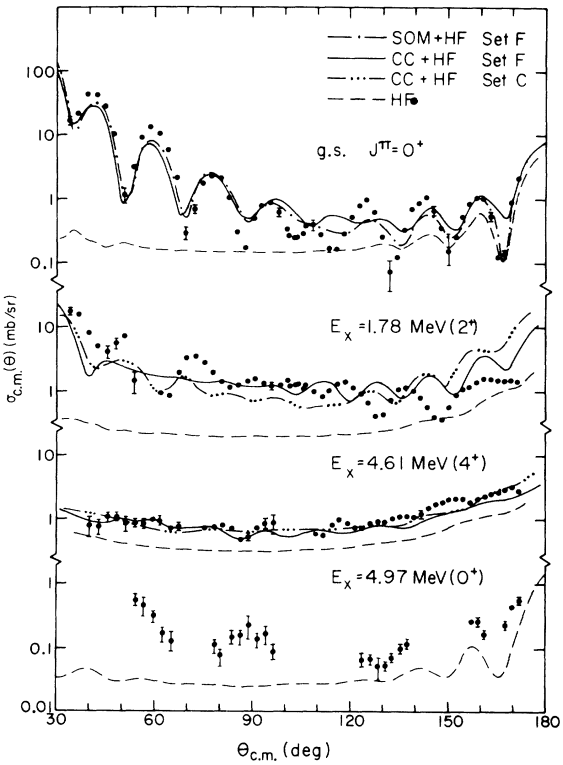

FIG. 6. Experimental energy-averaged angular distributions for the first four α-particle groups from ^{28}Si at a bombarding energy of 25.2 MeV. Spherical optical model (SOM), coupled-channel (CC), and Hauser-Feshbach (HF) predictions are shown as indicated. The potential parameters are listed in Tables I–III.

20 MeV in the real potential U over the range of well depths investigated, which was 20 to 200 MeV. Further automatic searches on the 25.2-, 26.2-, and 27.2-MeV elastic data were then carried out for several starting real-potential depths in the above range and with no HF contribution nor l dependence (LD), with HF and no LD, no HF and with LD, and with HF and LD. The parameters searched on were the real and volume imaginary potentials, the radius, the diffuseness, and where applicable, the density of spin-zero-states parameter ρ in the HF calculations and the l cutoff parameter l_c in the LD calculations. Allowing the real and imaginary radii and diffuseness to vary independently of each other produced no significant improvement in the fits and, therefore, these parameters were set equal. The spin distribution parameter σ was set equal to the rigid body value.[16] The fits with LD were only slightly better than without it. Surface absorption, given by the first derivative of the Woods-Saxon form factor (3), did not give as good agreement with the data as volume absorption.

The resulting parameters with HF and LD contributions are presented in Tables I and II as these gave the best over-all fits in the subsequent inelastic scattering analysis. These potentials are quite similar to those of Bobrowska *et al.*[7] where two groups of potential sets were found, corresponding to a large radius parameter and a small radius parameter. It is not clear whether this radius ambiguity is discrete or continuous (through a Vr^n relationship), since the diffuseness parameter corresponding to the two sets of radii is also different. Such a radius ambiguity was also observed for ^{27}Al + α scattering.[22] The value of the density of spin-zero states Γ_0/D_0 presented in Table II at each of the three bombarding energies is about one half of the predicted value[16] as this best fitted the data.

The direct contribution to the first three levels was then analyzed in the coupled-channels approximation with the computer code JUPITOR-1,[23] assuming a ground-state rotational band. A compound contribution was first subtracted from the data using the same values of σ and ρ [see Eq. (1)]

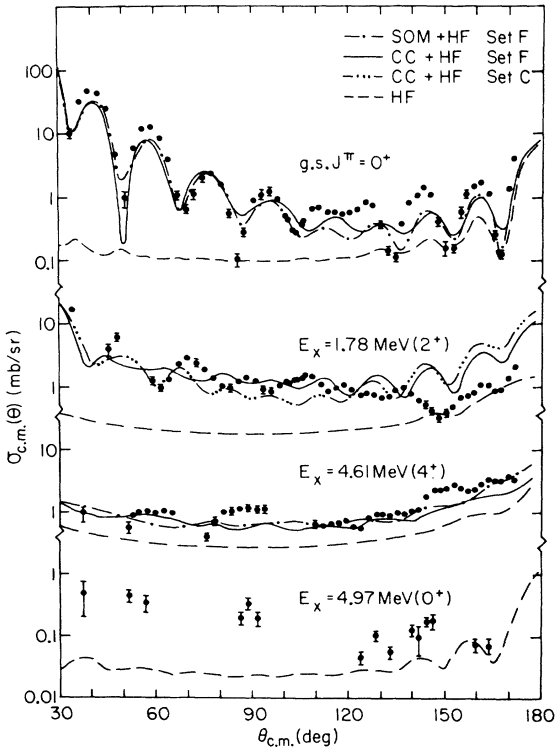

FIG. 7. Experimental energy-averaged angular distributions for the first four α-particle groups from ^{28}Si at a bombarding energy of 26.2 MeV. Spherical optical model (SOM), coupled-channel (CC), and Hauser-Feshbach (HF) predictions are shown as indicated. The potential parameters are listed in Tables I–III.

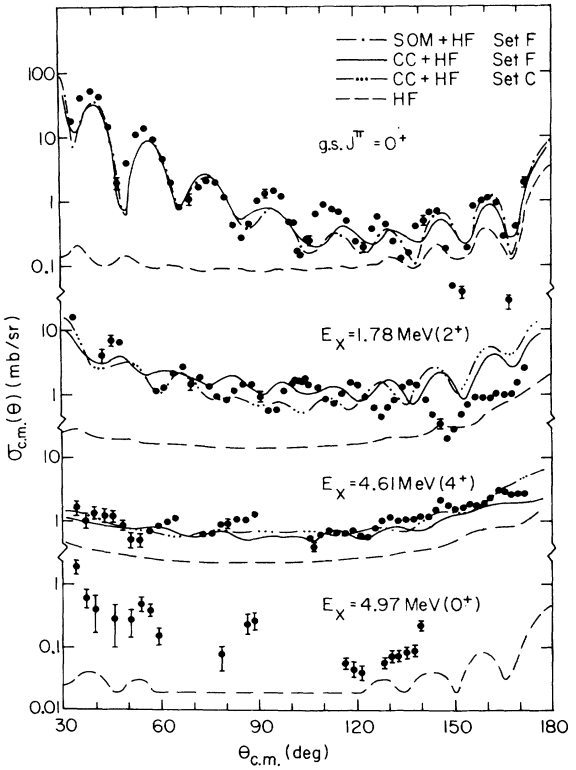

FIG. 8. Experimental energy-averaged angular distributions for the first four α-particle groups from ^{28}Si at a bombarding energy of 27.2 MeV. Spherical optical model (SOM), coupled-channel (CC), and Hauser-Feshbach (HF) predictions are shown as indicated. The potential parameters are listed in Tables I–III.

as for the elastic scattering, except that the width-fluctuation factor $W_{cc'}$ was set to two in the elastic channel and one in the nonelastic channels.[24] Parameter sets C and F (see Table III) were chosen initially for the coupled-channel analysis. The target was assumed to be axially symmetric and the Legendre polynomial expansion of the potential (2) with the radius $R = R_0(1 + \beta_2 Y_2^0 + \beta_4 Y_4^0)$ was made. Complex form factors were used in the calculation and Coulomb excitation was included. The imaginary potential was assumed to have a j-dependent term [Eq. (4)] rather than an l-dependent term since the spins of the excited states can couple with several different α-particle angular momenta.

The fitting procedure consisted of setting β_4 equal to zero and adjusting W and β_2 until optimum agreement was obtained for the ground and first excited states with $0^+, 2^+, 4^+$ coupling. The value of β_4 was then adjusted between -0.25 and $+0.25$ in an attempt to get agreement with the 4^+ state. The results are presented in Table III and Figs. 6–8.

The quality of the fits to the data is over-all poor. Extensive adjustments in the other parameters failed to improve agreement with the data. The sign and magnitude of β_2, or more correctly the deformation length[25] $\beta_2 R$, were determined unambiguously. Although the β_2 values listed in Table III differ appreciably, the products $\beta_2 R$ do in fact agree within the estimated uncertainty. The uncertainty in the β_2 values is due mainly to an ambiguity between the strength of the absorption W and β_2 – the more W is reduced, the smaller β_2 must be.

Values of the hexadecapole deformation in the range $-0.1 \leq \beta_4 \leq +0.1$ did not appreciably change the quality of the 4^+ fits to the data, while outside that range the calculations showed more pronounced structure than the data. Therefore, in the present energy range only an upper limit on the magnitude of β_4 could be determined; its sign and precise value is left indeterminate.

Several comments are in order here concerning the fitting procedure. First, it was not possible to keep the excited-state calculations in phase with the data over the entire angular range. Secondly, one could get somewhat improved fits to any one level over those shown in Figs. 6–8, but at the expense of the fits to the other two levels. This remark applies in particular to the 2^+ level, where better fits could be obtained by increasing β_2 and W, but then the fit to the elastic data became noticeably worse. Thirdly, the 4^+ data can be seen to slope upward more at the backward angles than the 2^+ data. Since the calculations for the excited states have about the same upward slope at the backward angles, it is clear that if one level is fitted at the backward angles, the other is not. If W is adjusted independently for each excited state, then the higher excited states would have a larger W and, hence, be damped more than the lower states.[23] This procedure would, therefore, worsen the fits to the 2^+ and 4^+ states. j dependence (included only in the diagonal terms of the potential) has the major effect on the slope at the backward angles and this was adjusted to compromise between the 2^+ and 4^+ data. Coulomb excitation was included and was found to have about a 10% effect on the calculations.

An attempt was made to fit the "direct" contribution to the first excited 0^+ state as a β vibration coupled to the lower-lying $K = 0$ rotational band. It was not possible, however, to maintain the proper magnitude of the cross sections in the other channels. This is consistent with the results of Huang, Gibson, and McDaniels,[26] who find that the 0^+ state at 4.97 MeV is not the band head of a rotational sequence, and also with the calculations of Castel and Parikh.[27]

TABLE I. Phase-equivalent optical-model potentials (U, W, r_0, a) and the normalized fitting criterion χ^2, averaged over the 25.2-, 26.2-, and 27.2-MeV data ($r_{\text{Coul.}} = r_0$).

Parameter set	U (MeV)	W (MeV)	r_0 (fm)	a (fm)	χ^2/N	Number of radial nodes
A	267	39	0.82	0.63	39	9
B	212	38	0.82	0.67	40	8
C	162	32	0.82	0.72	49	7
D	133	24	1.04	0.47	78	9
E	90	20	1.07	0.47	72	8
F	61	16	1.04	0.59	53	7
G	24	14	1.18	0.55	53	6

IV. CONCLUSION

The presence of a radius ambiguity observed in the present work makes the deformation parameter β_2 a less meaningful quantity than the deformation length[25] $\beta_2 R$. The average value of $\beta_2 = -0.26 \pm 0.08$ determined from Table III is consistent with the

TABLE II. l-dependent (j-dependent) absorption parameters and the Hauser-Feshbach parameters σ and Γ_0/D_0.

E_{lab} (MeV)	Δl (Δj)	l_c (j_c)	σ	Γ_0/D_0
25.2	2.	12.	3.21	630
26.2	2.	12.	3.24	860
27.2	2.	12.	3.27	1170

TABLE III. Coupled-channel potential parameters.

Parameter set[a]	U (MeV)	W (MeV)	r_0 (fm)	a (fm)	β_2	β_4	$\delta_2=\beta_2 R$
C	162	18.	0.82	0.72	-0.33 ± 0.05	$0.\pm0.1$	-1.25 ± 0.2
F	61	10.	1.04	0.59	-0.20 ± 0.05	$0.\pm0.1$	-0.96 ± 0.2

[a] See Table I.

results from the scattering of 104-MeV α particles[1] and 250-MeV electrons.[28] The large uncertainty of ±0.08 quoted here includes an uncertainty due to the compound contribution to the 2^+ state, which accounts for about 20% of the 2^+ cross section and is believed to be accurate to within a factor of 2.

Although the compound contribution to the 4^+ state accounts for about 30% of the cross section, this does not directly affect the uncertainty on β_4 since for $|\beta_4|>0.1$ the calculation takes on more pronounced structure than is evident in the data. It seems in fact that no hexadecapole deformation is necessary to describe the data and that it is, therefore, impossible to extract a β_4 value for ^{28}Si with α particles at tandem energies. This seems to be in contrast to the situation at 104 MeV, where the 4^+ angular distributions display more pronounced structure. The direct contribution (70%) to the first excited 0^+ state at 4.97 MeV cannot be explained by a simple collective-model oscillation, in agreement with other experiments,[26] and theoretical calculations.[27]

As can be seen in Figs. 6–8, the quality of the fits for the two types of potentials (large radius and small radius) is about the same. Although not shown here, calculations with the other potential parameter sets corresponding to different numbers of radial nodes produced the same quality of fits, also leading to the above conclusions. This result is consistent with Eberhard and Robson's[29] conclusion that it is not possible to distinguish between phase-equivalent ambiguities with such coupled-channel calculations at low energies.

Although it is not certain why the lower energy α-particle scattering measurements are insensitive to a hexadecapole deformation, a longer de Broglie wave length or the presence of compound nuclear processes[30] might be expected to mask such a deformation. ^{3}He scattering can be used to test the effects of compound nuclear processes, since in that case such processes are expected to be reduced due to the lower binding energy of ^{3}He. Some recent excitation-function measurements of ^{3}He + ^{28}Si by Dehnhard and Chant[31] at 23 to 27 MeV seem to verify this expectation. Unfortunately, β values were not extracted in that work. A coupled-channel analysis of ^{3}He scattering from ^{20}Ne at 17.8 MeV, where little compound contribution is also expected, is not able to describe the 4^+ excitation and a nonzero β_4 gives more structure to the calculation than is present in the data.[32] This is in contrast to 104-MeV α-particle scattering from ^{20}Ne, where $\beta_4=+0.11\pm0.01$.[1] In fact, in the ^{3}He and α-particle scattering from both ^{20}Ne (Refs. 1 and 32) and ^{28}Si (Ref. 31) there appears no angular structure in the 4^+ excitation at the lower energies while a nonzero β_4 produces structure. It is, therefore, possible that the strong absorption of ^{4}He and ^{3}He projectiles is responsible for masking hexadecapole deformations in s-d shell nuclei at the lower energies. In a heavier target, on the other hand, the hexadecapole deformation might be expected to be confined more to the surface, since more nucleons are present, and ^{4}He and ^{3}He projectiles, with their intrinsically high angular momenta, would be able to excite higher multipole moments more effectively. This has been demonstrated for α-particle scattering on several rare-earth nuclei at $E_\alpha\simeq30$ MeV, where moments up through Y_6 were extracted.[33]

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