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# Alpha-Particle Scattering and Production of an Unnatural-Parity State in $\mathrm{Si}^{28}$[†]

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Alpha-particle scattering from $\mathrm{Si}^{28}$ has been studied at six bombarding energies between 16.2 and 27.0 MeV. Angular distributions for scattering from the ground and four excited states are presented at each energy, and total cross sections are obtained from these differential cross sections. Because the unnatural-parity excited state at 6.27 MeV cannot be excited by alpha-particle scattering under direct-interaction conditions, special attention was paid to measuring the angular distribution of the cross section for production of this state. The angular distribution itself does not provide any unambiguous indication of the reaction mechanism responsible for production of the 6.27-MeV state; identification of the mechanism will require a full theoretical analysis of these data.

## INTRODUCTION

An unanswered question in the study of nuclear reactions is the nature of the mechanism by which alpha-particle scattering excites unnatural-parity states in spinless nuclei. Unnatural-parity states are defined as energy levels whose parity does not equal $(-1)^J$, where $J$ is the total spin of the state. Eidson and Cramer[1] have shown that these states cannot be produced by means of a direct interaction between an alpha particle and a spinless nucleus. However, a few experimenters have observed that alpha-particle scattering does excite unnatural-parity states in spinless nuclei and that this excitation occurs with measurable cross section.[1–5] To explain the observed cross sections Eidson and Cramer have suggested four nondirect reaction mechanisms for excitation of the unnatural-parity states. Eidson and Cramer's own data indicate that probably only two of the four mechanisms can account for the observed cross sections; these two mechanisms are (1) an exchange process, e.g., knockout, and (2) multiple excitation by production of two or more phonons in successive steps.[6] It is, however, difficult to choose between these processes on the basis of the available data, and a careful study of the cross section's variation with alpha-particle energy may help to identify the reaction mechanism.

In the $\mathrm{Si}^{28}$ level structure (Fig. 1) there is a $3^+$ state at an excitation of 6.37 MeV.[7] The present experiment was undertaken principally to study how the production of this unnatural-parity state varies with bombarding alpha-particle energy. Before this work there existed only two angular distributions for excitation of this state by alpha scattering: the Eidson and Cramer measurement at 22.5 MeV[1] and one by Kokame *et al.* at 24.8 MeV.[2] This article reports additional angular distribution measurements at six bombarding energies between 16.2 and 27 MeV.

There is a second reason for undertaking a study like this one: In the energy range covered by this experiment few data exist for alpha-particle scattering, even from natural-parity states. To study how the reaction properties—optical-model parameters, for example—vary with bombarding energy it is usually necessary to compare absolute cross sections measured in separate experiments at different laboratories. This kind of comparison can easily mask small variations with energy simply because uncertainties in absolute cross sections tend to be large. Since all the cross sections studied in this experiment were measured with the same target and detectors, variations with bombarding energy are revealed by variations in relative cross sections. In addition, then, to the data for the 6.27-MeV excited state this report presents similar angular distributions for the other states indicated by an asterisk in Fig. 1.

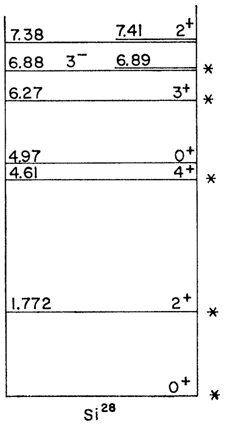

FIG. 1. Energy-level diagram of $\mathrm{Si}^{28}$ below 7.41 MeV. Levels studied in the present experiment are marked with an asterisk. The level spacings (in MeV) and spin assignments are taken from Refs. 7 and 8. The odd parity assigned to the 6.88-MeV level has not been conclusively established.

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## EXPERIMENTAL PROCEDURE

Although this experiment represents the first use of the University of Illinois cyclotron's variable-energy alpha beam, the principal features of the experimental arrangement used to take these data have been previously described.[9] The only significant difference from the description in Ref. 9 is that two surface barrier devices were used simultaneously to detect alphas scattered from the silicon target. These detectors viewed the target at laboratory scattering angles approximately 135° apart. Collimators in front of the detectors restricted their angular acceptance to ±0.44° for the detector used at forward angles and ±0.89° for the detector used at back angles. At the higher scattering angles and lower bombarding energies these detectors were capable of stopping protons from $(\alpha,p)$ reactions on $\mathrm{Si}^{28}$ and on target contaminants.

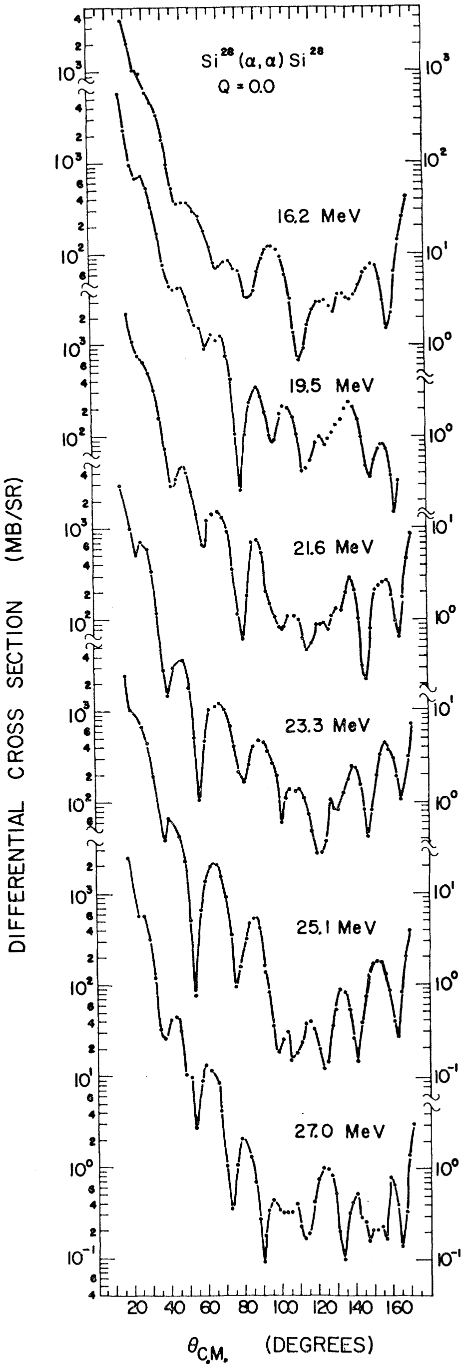

FIG. 2. Angular distributions for alpha scattering from the ground state of $\mathrm{Si}^{28}$ at six bombarding energies. Uncertainties in relative cross sections are generally smaller than the data points shown.

The beam energy was measured by observing the pulse heights produced in one of the detectors by elastically scattered alphas. These pulse heights were compared with those produced in the same detector by 8.78-MeV alphas from a natural source. The accuracy of the beam-energy determination was about ±2%.

The target was a self-supporting foil prepared by electron bombardment of high-purity natural silicon. The silicon was evaporated onto a copper backing which was etched away by careful dipping into an acid bath[10]; the remaining silicon foil was then cleaned in distilled water. The target thickness, determined by measuring the energy loss of 8.78- and 6.05-MeV alpha particles in penetrating the foil, was 0.14 mg/cm$^2$. The target was deliberately made quite thin in order to avoid the energy resolution difficulties that have been cited[2] as causing difficulty in observing the 6.27-MeV state in $\mathrm{Si}^{28}$. The target was somewhat nonuniform; in the area bombarded by the beam there was a variation in the thickness of approximately 5%.

Carbon and oxygen contaminants in the silicon foil were present in large enough amounts to cause, at some scattering angles, serious interference between alphas scattered from silicon and alphas scattered from contaminants. The subtraction of these impurity groups from the silicon spectra was performed with the help of angular distributions for the $\mathrm{C}^{12}+\alpha$ and $\mathrm{O}^{16}+\alpha$ reactions. These contaminant angular distributions were measured under the same conditions as the silicon data: Whenever alpha-particle spectra from the silicon target had been taken at two successive scattering angles, a spectrum was measured for alpha scattering from a thin foil of Mylar, which contains substantial amounts of carbon and oxygen.

Cross sections were extracted from the raw data by the data-handling methods described in Ref. 9. Most of the computer analysis was performed with the Sandia Corporation CDC 3600 facility.

The total uncertainties in the relative-cross-section measurements are shown by bars on the angular distribution graphs presented in this paper. These indicated errors represent combined uncertainties in the

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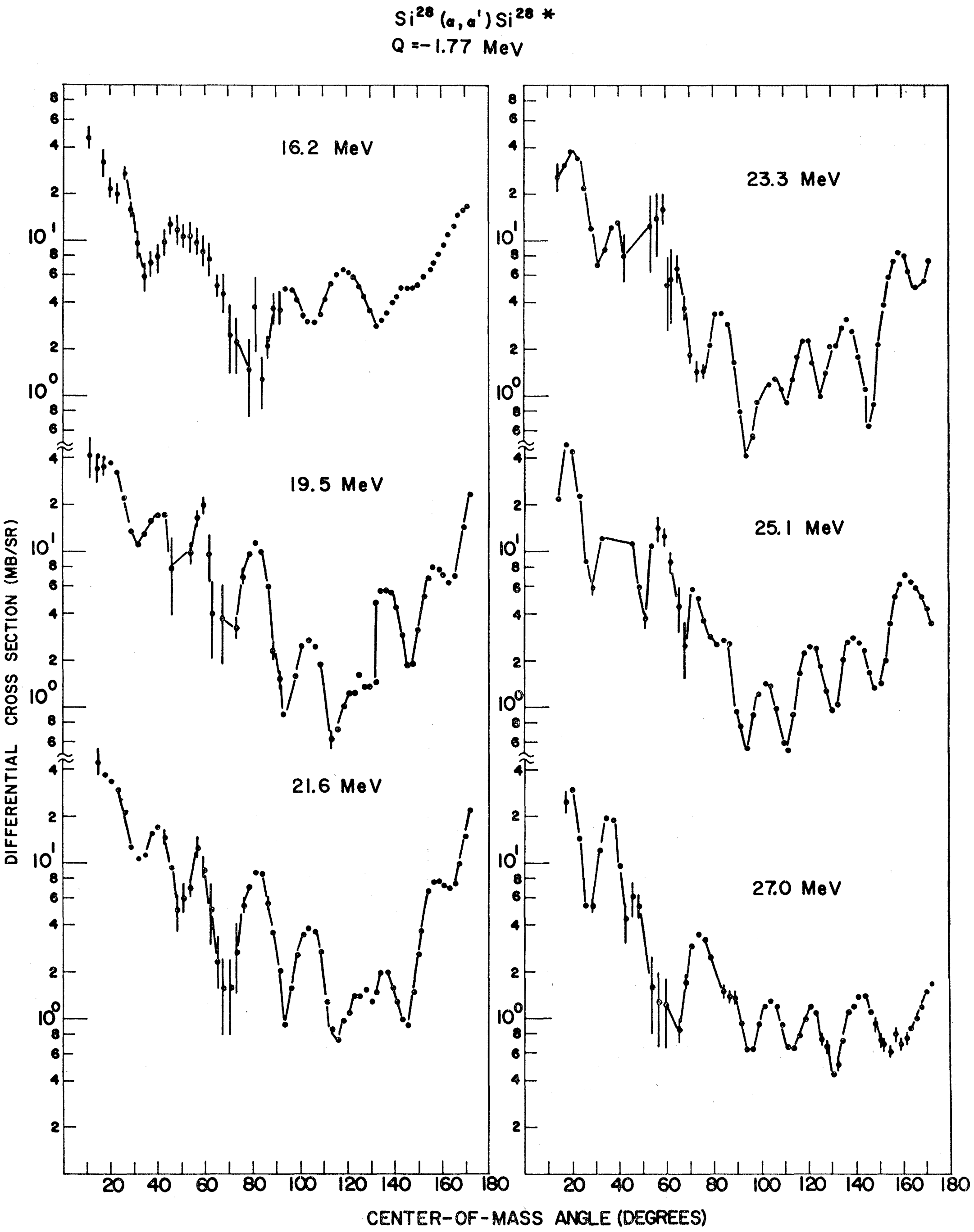

FIG. 3. Angular distributions for alpha scattering from the first excited state of $Si^{28}$. The error bars indicate total uncertainties in the relative differential cross sections as explained in the text. Where not indicated by bars, these uncertainties are smaller than the size of the data points.

counting statistics, in contaminant and general background subtractions, and in the target angle measurements. The largest contribution to error arises from the uncertainties in contaminant subtractions. Where no error bars are shown on the graphs, the rage of uncertainty is smaller than the dot representing the cross section. The errors in the absolute cross sections for the elastic-scattering measurements are approximately ±10% and are due primarily to the uncertainty in the target thickness measurement.

## RESULTS

### Natural-Parity States

Figures 2 and 3 present, respectively, cross-section angular distributions for scattering from the ground and first excited states of $Si^{28}$. The familiar oscillatory patterns are present, and the cross sections decrease with increasing bombarding energy.

Figure 4 displays the angular distributions for scattering from the 4.61-MeV state. Although the contaminant subtraction errors affect the cross sections rather severely, it is still possible to discern an oscil-

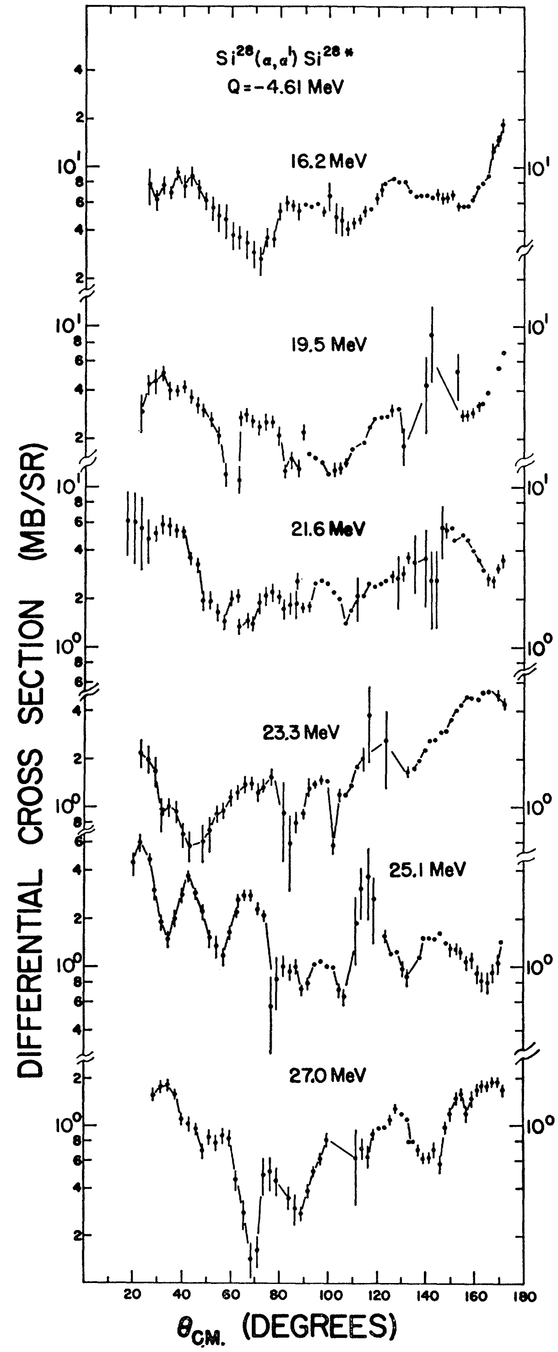

FIG. 4. Angular distributions for alpha scattering from the second excited state of $Si^{28}$. See Fig. 3 caption for explanation of the error bars.

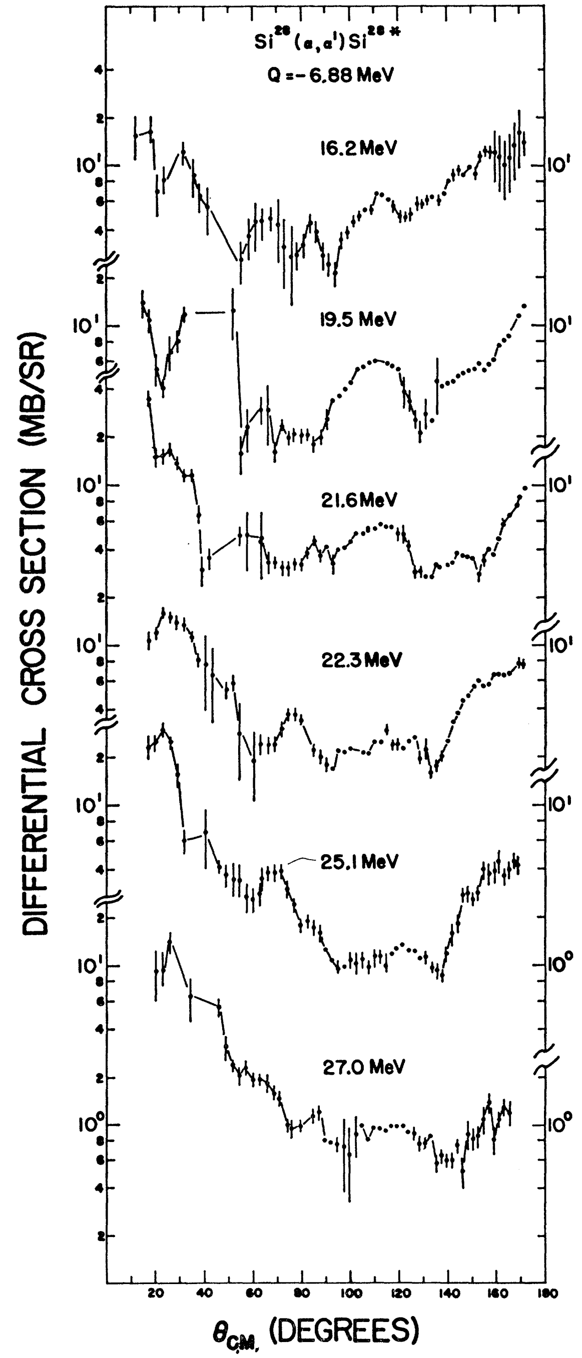

FIG. 5. Angular distributions for alpha scattering from 6.88-MeV excited state of $Si^{28}$. See Fig. 3 caption for explanation of the error bars.

latory structure. A nearby state at 4.97-MeV excitation (Fig. 1) was observed at many angles during the experiment. Because this state was excited only weakly, no complete angular distributions could be measured for it. It was, however, always well resolved from the 4.61-MeV state.

Figure 5 presents data for excitation of both members of the 6.88-MeV doublet, which was not resolved in any of the spectra. These distributions are less sharply oscillatory than those for the lower lying natural-parity states, and it is difficult to determine any clear phase relationship with the ground-state oscillations. However, the weak diffraction patterns in Fig. 5 do tend to be out of phase with the ground-state patterns shown in Fig. 2. Interpreted by the phase rule for direct interactions,[11] this tendency would indicate that the 6.88-MeV state has even spin, in disagreement with the accurate measurement reported in Ref. 8. If, however, the state is produced through a nondirect interaction, the data would not necessarily imply such a contradiction.

### Unnatural-Parity State

Figure 6 displays the angular distributions for the unnatural-parity state at 6.27-MeV excitation. At each bombarding energy there are gaps in the data at the angles where alpha particles scattered from the ground and first excited states of $C^{12}$ had nearly the same energies as those scattered from the 6.27-MeV state. At the two highest energies the $O^{16}$ ground-state group

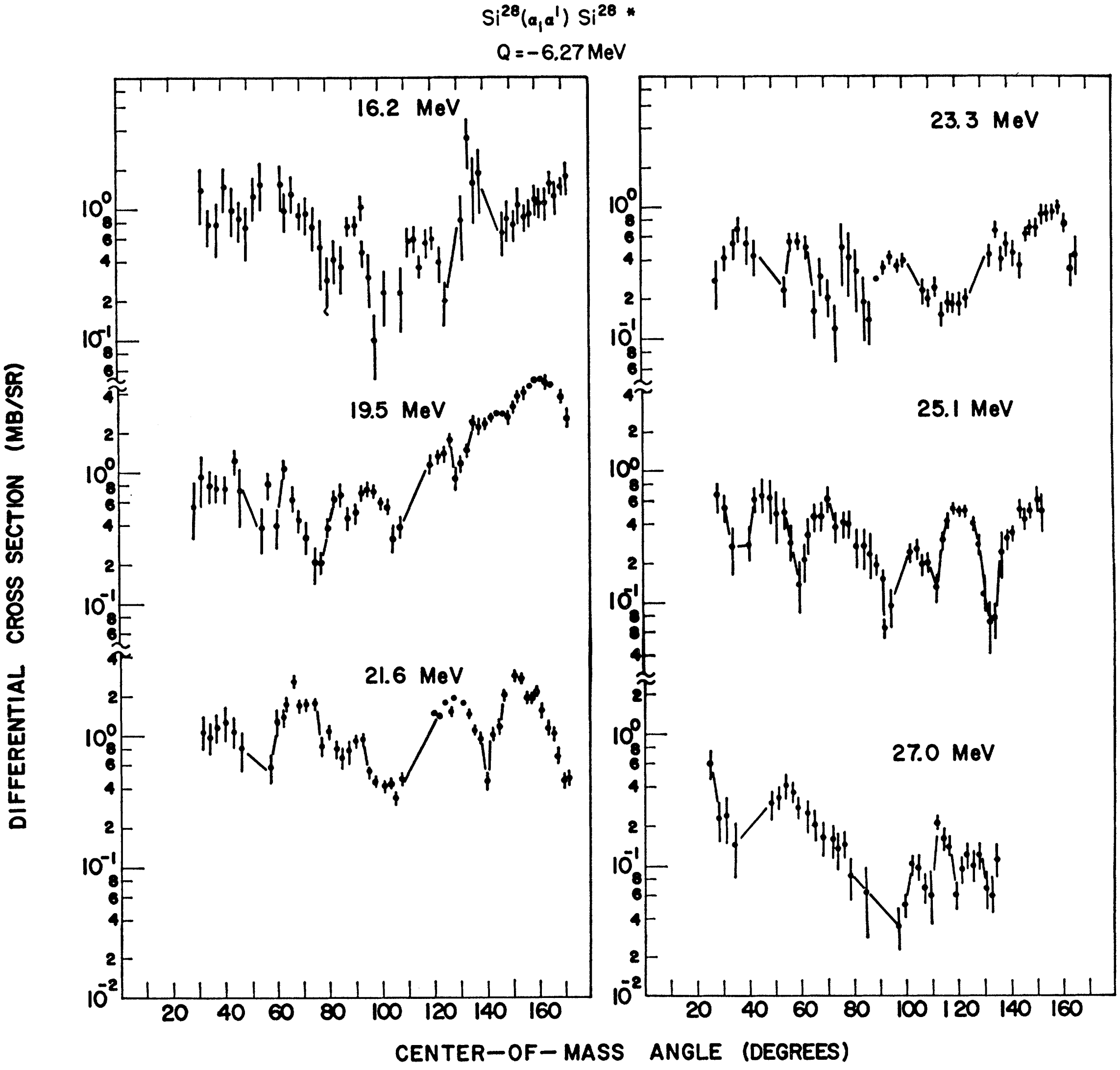

FIG. 6. Angular distributions for alpha scattering from the unnatural-parity (3+) state in $Si^{28}$. See Fig. 3 caption for explanation of the error bars.

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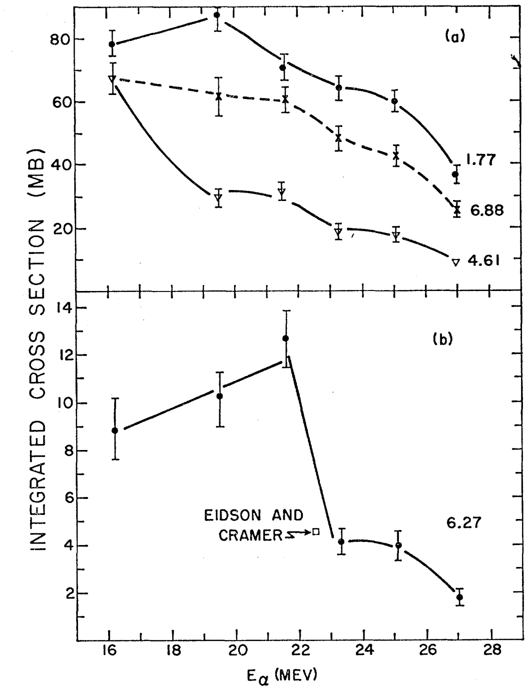

FIG. 7. (a) Total cross sections for scattering from three natural-parity excited states in $Si^{28}$ as a function of bombarding energy. (b) Energy dependence of the total cross section for scattering from the unnatural-parity $(3^+)$ state in $Si^{28}$. Error bars in both parts of this figure indicate total uncertainties in the relative values of the cross sections.

obscured the unnatural-parity-state group at the largest angles. These contaminant alpha-particle groups were in general much more intense than those from the weakly excited unnatural-parity state; accordingly, subtractions were difficult to make with any accuracy.

In spite of these shortcomings the data clearly show the oscillatory behavior that characterized the other $Si^{28}$ states studied in this experiment. Unfortunately, the phase relationship between the diffraction patterns shown in Fig. 6 and in Fig. 2 is not at all clear. The oscillations at energies above 23.3 MeV do show a barely discernible tendency to be out of phase with the ground state, but they do not furnish any firm support for a conclusion, based on the phase rule, that the state is therefore produced by multiple excitation.

Clearer information about the production of the 6.27-MeV state is contained in Fig. 7. Here are displayed for each excited level in $Si^{28}$ total cross sections obtained by taking the integral

$$2\pi\int (d\sigma/d\Omega)\,\sin\theta\,d\theta$$

over the angular distributions in Figs. 2–6; here $d\sigma/d\Omega$ is the differential cross section and $\theta$ is the center-of-mass scattering angle. Also shown is the total cross section obtained by integrating Eidson and Cramer's published differential cross sections[1] for production of the 6.27-MeV state. A total cross section cannot be computed from the differential cross sections of Kokame *et al.*[2] because those measurements were made only between 17° and 78° in the center-of-mass system. Over that angular range, however, Kokame's cross sections (at 24.8-MeV bombarding energy) are of roughly the same magnitude as those shown in Fig. 6 at the three highest bombarding energies. Thus there appears to be no serious disagreement between Kokame's data and the total cross sections presented in Fig. 7.

In the upper half of Fig. 7 the total cross sections for the natural-parity states show a nearly monotonic decrease with increasing bombarding energy. In sharp contrast the unnatural-parity cross section, displayed in the lower half of the figure, rises slowly up to the 21.6-MeV value and then drops sharply. It is interesting to compare this behavior with Satchler's prediction, quoted by Eidson and Cramer,[1] that cross sections for formation of an unnatural-parity state by a knockout mechanism should decrease rapidly above 20 MeV. The data in Fig. 7 thus suggest that a knockout mechanism may be responsible for production of the $3^+$ level in $Si^{28}$.

However, these data by no means decide the question of the reaction mechanism that produces the $Si^{28}$ unnatural-parity state. The very least that will be required before the matter can be settled is a full-scale theoretical analysis using both exchange and multiple-excitation formalisms. It is hoped that the data presented here will aid such an investigation.