state in ^{25}Mg and of the four lowest excited states in ^{55}Fe. In addition, Doppler shifts were measured for 0.87-MeV γ rays from ^{17}O nuclei and the 0.58-MeV γ rays in ^{25}Mg nuclei recoiling in krypton. Since the mean lives of both of these states are well known, the results could be used to show that for the range of velocities used, the slowing down of ^{17}O in krypton and of ^{25}Mg in krypton are consistent with the calculations of LSS[8] to al least 6 and 12%, respectively. This may indicate that the theory of LSS works better for calculations of an integrated value of dE/dx for ions slowing down in krypton than it does for calculations of dE/dx at a given velocity for ions slowing down in lighter elements.[18] However, the data presented here are certainly too few to allow definite conclusions about this matter.

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Energy Dependence of the Reorientation Effect and the Static Quadrupole Moment of the 0.847-MeV 2$^+$ State in Fe^{56}†

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The energy dependence of the reorientation effect has been investigated using O^{16} and S^{32} ions incident on Fe^{56} nuclei. The influence of nuclear interference on the reorientation effect was observed before it could be detected on the elastic cross section, and exhibited an angular dependence similar to that expected for the reorientation effect. It was found that an appropriate separation of projectile and target nuclei was given by $2a = R_0(A_1^{1/3} + A_2^{1/3}) + \Delta$, where $R_0 = 1.6$ fm and $\Delta \geq 3.5$ fm. The static quadrupole moment of the 0.847-MeV 2$^+$ state in Fe^{56} was measured to be $Q_{22} = -0.23 \pm 0.03$ b, while the rotational value is given by $|Q_R| = 0.276$ b.

I. INTRODUCTION

In recent years the reorientation effect[1] has been used to measure a large number of static quadrupole moments of first excited 2$^+$ states of even-even nuclei, using various experimental techniques (for example, see Refs. 2–11). However, the unambiguous interpretation of the reorientation effect depends sensitively on the experimental conditions in the individual experiments. In order to realize the full potential of the reorientation effect as a method of determining static quadru-

pole moments a number of questions need to be answered by experiment:
(1) What experimental conditions are required so that the effect of the nuclear force is entirely negligible?
(2) What combination of measurements is required to accurately determine the sign and magnitude of contributions from higher states?
(3) What is the magnitude of the interference effects between the direct Coulomb excitation of the excited state and the excitation of the excited state via the giant dipole resonance?
(4) How can the reorientation effect be "calibrated" or cross-checked with other methods of measuring nuclear quadrupole moments?

In order to separate these difficulties a search was conducted for a nucleus where a substantial reorientation effect occurs, and where multiple Coulomb excitation effects are negligible. Then it would be possible to study the energy dependence and the projectile dependence of the reorientation effect. The energy dependence for a particular projectile and target would give detailed information about the "safe" bombarding energy. Self-consistency of the reorientation effect as a function of the projectile can give information about the presence of contributions from higher states in those cases where nearby states exist.[12] For target excitation, theoretical estimates indicate that the fractional contribution of excitation via the giant dipole resonance to the observed deviation from first-order Coulomb excitation is essentially independent of the projectile type. Model-dependent calculations also indicate that the contribution is negligible for the present experiments.[13] We have carefully studied the energy dependence of the reorientation effect of the 0.847-MeV 2^+ state in Fe^{56}, using O^{16} as a projectile in the energy range from 22 to 40 MeV.

The self-consistency of the lower-energy results was cross-checked using S^{32} as a projectile. The Fe^{56} nucleus was chosen because a substantial reorientation effect is known to occur[8] and higher-state contributions are negligible.

II. EXPERIMENT

The static quadrupole moment Q_{22} of the first excited 2^+ state of an even-even nucleus can be determined by measurements of the relative excitation probability $P_{if}(\xi, \theta_{\text{Ion}})$ as a function of projectile ion scattering angle,[14] where ξ is the adiabaticity parameter. The relative excitation probability may be evaluated using the relation

$$P_{if}(\xi, \theta_{\text{Ion}}) = \frac{d\sigma_{if}}{d\Omega}\,(\text{inelastic}) \Big/ \frac{d\sigma_R}{d\Omega}\,, \qquad (1)$$

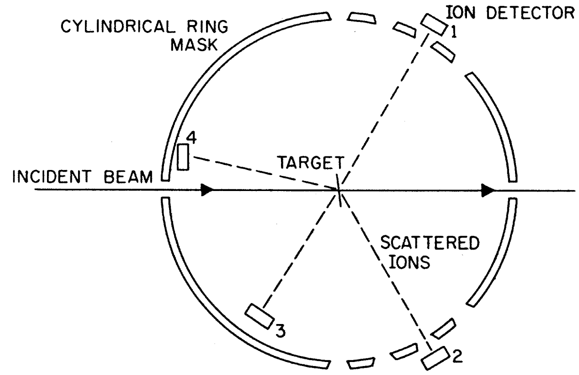

FIG. 1. Schematic diagram of arrangement of particle detectors in the scattering chamber.

where $d\sigma_R/d\Omega$ is the Rutherford cross section. We have chosen to measure the relative excitation probability as a function of ion scattering angle and to identify the inelastic events by requiring a coincidence between a deexcitation γ photon and a scattered ion.

The deexcitation γ photons were detected in a 22.85-cm-diam × 10.15-cm-thick NaI(Tl) crystal positioned with the front face of the crystal 3.18 cm from the target. The crystal symmetry axis was placed directly above the target center and perpendicular to the scattering plane. The crystal was physically rotated about its symmetry

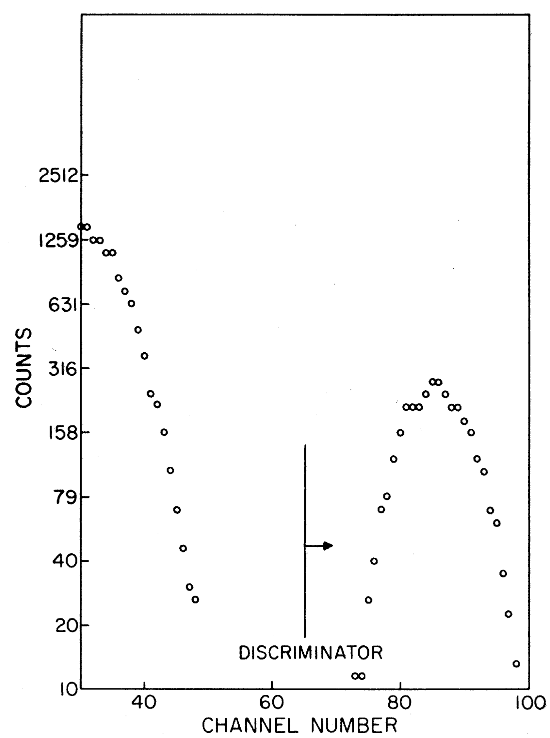

FIG. 2. Ion-detector spectrum at 60° in the laboratory for 56-MeV S^{32} projectiles incident on Fe^{56}.

axis during the experiment to average out any Φ_γ asymmetry in the crystal efficiency.

In order to perform the experiment most efficiently and to cover a large range of ion scattering angles, ions were detected simultaneously in four ion detectors placed at different angles in the ion scattering plane. The excitation probability is extremely sensitive to the scattering angle for forward scattering, so that the scattering angle must be accurately known. We have constructed a cylindrical ring with a 26-cm diam, behind which two ion detectors can be positioned symmetrically with respect to the beam axis at laboratory scattering angles of 90, 75, 60, and 45°. This cylindrical ring is aligned with respect to the scattering chamber center and incident beam direction. Using a transit, which sights along the beam line, the target is positioned with respect to the chamber center with an accuracy of ±0.3 mm. Calibration of the detectors with respect to the ion scattering angle is achieved by moving the detectors into the transit line of sight and noting the corresponding angle setting. The various circular apertures in the cylindrical ring are 1.54 cm in diameter, while the surface-barrier detectors, which are positioned behind these apertures, have a sensitive surface with a diameter of 2.39 cm. Thus, slight detector positioning uncertainties can be tolerated while retaining angle integrity. In the backward angles it is preferable to place detectors closer to the target. Inside the 26-cm cylindrical ring a third detector with its sensitive surface individually masked to a diameter of 1.9 cm is positioned at 7.5 cm from the chamber center. This detector is moved over a range from 100 to 145° in the laboratory. The fourth detector, with a sensitive surface of 2.39 cm in diameter, is fixed 7.50 cm from the chamber center at a laboratory scattering angle of 162°. The chamber arrangement is shown schematically in Fig. 1.

In order to continuously monitor the angle integrity during the reorientation experiments, the total number of scattered ions in each of the four detectors is compared with the Rutherford cross section. Deviations from the Rutherford cross section are interpreted as a change in the beam position and are used to correct the data. Expressed in angular terms these variations reflect uncertainties of <0.2° for the individual forward counters. The corrections thus further reduce the angle uncertainties.

The ion counters were used to gate the γ detector. Thus a real-plus-accidental and accidental γ spectrum are recorded for each ion detector. The details of the electronic arrangement have been described in an earlier paper.[12] A typical ion spectrum and ungated γ spectrum are shown in Figs. 2 and 3.

The targets were in the form of self-supporting Fe metal films ~200 $\mu g/cm^2$ thick. Naturally abundant Fe, which contains 91.7% Fe^{56}, was evaporated from an Al_2O_3-coated Mo boat onto glass sub-

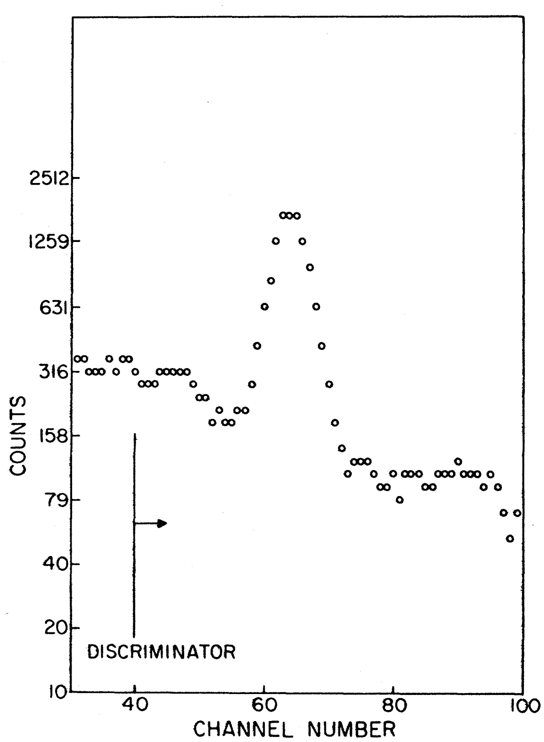

FIG. 3. γ-ray detector spectrum for 56-MeV S^{32} projectiles incident on Fe^{56}.

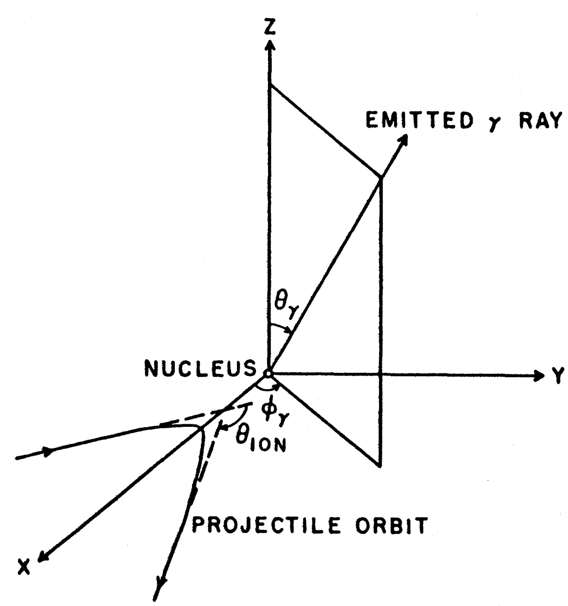

FIG. 4. Focal coordinate system.

strates heated to 200℃. The glass slides had previously been coated with a release agent, KCl, by evaporation. After evaporation of the Fe the slides were heated to 350℃ in order to anneal the films. The films were floated onto water and then lifted onto copper target holders which had a 0.635-cm circular aperture.

III. TREATMENT OF DATA

The output from a reorientation effect experiment, for a given set of ion angles, consisted of the eight gated γ spectra and the total number of scattered ions in each detector. The γ spectra were processed to determine the number of real, R_i, γ rays in the photopeak coincident with ions in detector i, where $i=1$ to 4. The small fraction of real coincidence events under the photopeak due to higher-energy γ rays from target impurity decays was determined and subtracted. The number of ions from detector i was denoted as N_i. The kinematical corrections were combined in the quantity $D_i(\theta_{\text{Ion}})$ which includes corrections for isotopic impurities in the target which affects the total cross section. Typically, four measurements were made at each of four sets of scattering angles. The 162° position was repeated each time. At least 4000 real coincidences were measured at each angle. The relative excitation probability $P_{if}(\xi, \theta_{\text{Ion}})$ was obtained from

$$P_{if}(\xi, \theta_{\text{Ion}}) = R_i D_i(\theta_{\text{Ion}})/N_i C_i(\xi, \theta_{\text{Ion}}), \quad (2)$$

where $C_i(\xi, \theta_{\text{Ion}})$ is the relative crystal correction to be discussed below.

The excitation probability was parametrized as

$$P(\theta_{\text{Ion}}) = A(\theta_{\text{Ion}}) + M_{22}B(\theta_{\text{Ion}}), \quad (3)$$

where M_{22}, the reduced matrix element, is related to Q_{22} by $eQ_{22} = -0.753M_{22}$. The theoretical excitation probability was calculated using M_{22} values which straddle the experimental curve, with the aid of the Winther–de Boer[15] computer program. A least-squares fit to the experimental points was then made to obtain M_{22}.

The origin of the relative crystal correction $C(\xi, \theta_{\text{Ion}})$ is the variation of the anisotropic particle-γ angular distribution with the ion scattering angle. Consider the focal coordinate system shown in Fig. 4. The large γ-crystal axis is situated along the z axis above the ion scattering plane. After integrating over the Φ_γ dependence, the angular distribution of the deexcitation photons seen by the large γ crystal in the focal system can be

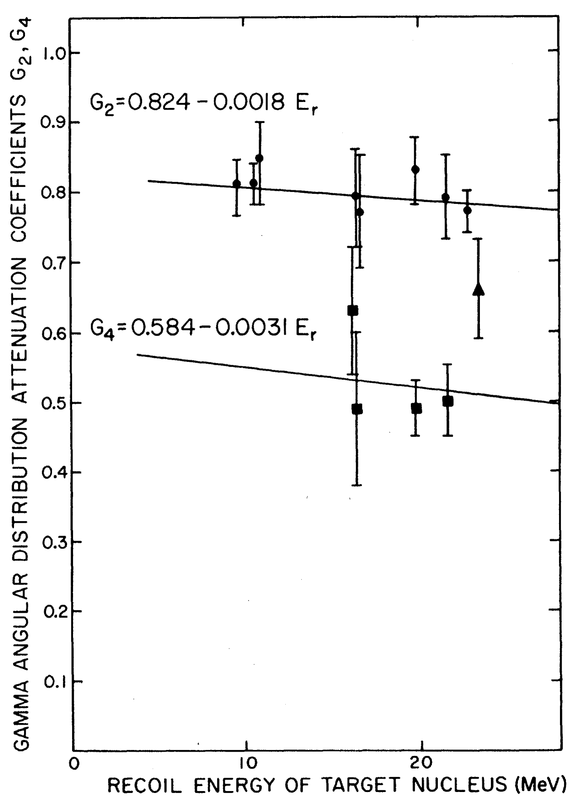

FIG. 5. γ-ray distribution attenuation coefficients for Fe^{56}.

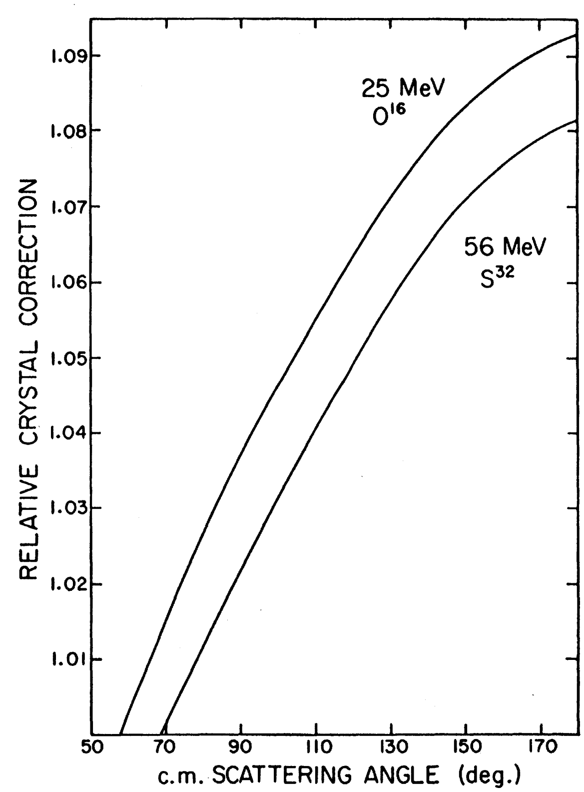

FIG. 6. Relative crystal correction, $C(\xi, \theta_{\text{Ion}})$, for the 0.847-MeV state of Fe^{56}.

written

$$W(\theta_{\mathrm{Ion}}, \theta_\gamma, \xi) = 1 + G_2(\theta_{\mathrm{Ion}}) A_2(\theta_{\mathrm{Ion}}, \xi) P_2(\cos\theta_\gamma) + G_4(\theta_{\mathrm{Ion}}) A_4(\theta_{\mathrm{Ion}}, \xi) P_4(\cos\theta_\gamma)\,, \quad (4)$$

where θ_{Ion} is the ion scattering angle, θ_γ is the angle of emission of the deexcitation photon with respect to the z axis, and ξ is the adiabaticity parameter. The $P_k(\cos\theta_\gamma)$ are Legendre polynomials, and the $A_k(\theta_{\mathrm{Ion}}, \xi)$ are proportional to the statistical tensors for the distribution. The $G_k(\theta_{\mathrm{Ion}})$ are the attenuation coefficients.

If the excited target nucleus recoils out of the target before decay occurs, the nucleus can be subject to large electric and/or magnetic fields at the nucleus due to ionization of the atomic electron shell. These fields can interact with the nuclear moments and cause precession of the angular momentum vector of the excited nuclear state before decay. Since the degree of ionization of the atomic electron shell can depend on the recoil energy, the amount of precession can depend on the incident-ion scattering angle. The precession results in attenuation of the γ angular distribution as manifested in the attenuation coefficients $G_k(\theta_{\mathrm{Ion}})$.

The crystal correction $C(\xi, \theta_{\mathrm{Ion}})$ compensates

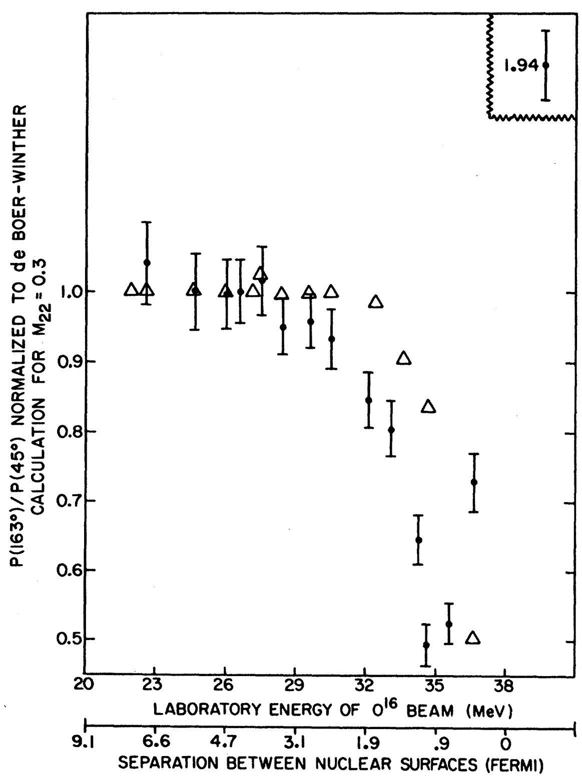

FIG. 7. Effect of the nuclear interference on Coulomb excitation for O^{16} projectiles exciting the 0.847-MeV state of Fe^{56}.

for the differences in the photon angular distributions for different scattering angles. The correction is the relative probability that the emitted γ ray due to an excitation from a particle scattered to θ_{Ion} is captured as a photopeak event in the NaI(Tl) crystal. The correction can thus be written

$$C(\xi, \theta_{\mathrm{Ion}}) = \frac{\int_0^\pi W(\theta_\gamma, \theta_{\mathrm{Ion}}, \xi)\epsilon(\theta_\gamma)\sin\theta_\gamma d\theta_\gamma}{\int_0^\pi W(\theta_\gamma, \theta_{\mathrm{Ion}}, \xi)\sin\theta_\gamma d\theta_\gamma}\,, \quad (5)$$

where $\epsilon(\theta_\gamma)$ is the relative photopeak efficiency of the crystal. The denominator in Eq. (5) is a normalization constant. The integration can be performed and the crystal correction can be written

$$C(\xi, \theta_{\mathrm{Ion}}) = 1 + G_2(\theta_{\mathrm{Ion}}) H_2(\xi, \theta_{\mathrm{Ion}}) + G_4(\theta_{\mathrm{Ion}}) H_4(\xi, \theta_{\mathrm{Ion}})\,, \quad (6)$$

where the quantities H_k are combinations of the $A_k(\xi, \theta_{\mathrm{Ion}})$ and the integrals $\int_0^\pi P_k(\cos\theta_\gamma)\epsilon(\theta_\gamma) \times \sin\theta_\gamma d\theta_\gamma$. The $A_k(\xi, \theta_{\mathrm{Ion}})$ are evaluated using the Winther–de Boer program. These parameters are quite insensitive to M_{22} so that the crystal correction is also insensitive to M_{22}. The relative photopeak efficiency $\epsilon(\theta_\gamma)$ was measured as a function of γ-ray energy and interpolated to the energy of the γ ray detected in the experiment. No Φ_γ asymmetry was detected. The quantities H_k were then evaluated using a numerical integration. For the experimental geometry used here, $H_4(\theta_{\mathrm{Ion}}, \xi) \ll H_2(\theta_{\mathrm{Ion}}, \xi)$. Because of this the important quantity to be determined is $G_2(\theta_{\mathrm{Ion}})$.

To measure the values $G_2(\theta_{\mathrm{Ion}})$ and $G_4(\theta_{\mathrm{Ion}})$ [or equivalently $G_2(E_{\mathrm{recoil}})$ and $G_4(E_{\mathrm{recoil}})$], we measured the angular distribution of the γ radiation with respect to the incident-particle direction using a 3.82-cm-diam×2.54-cm-thick NaI(Tl) crystal. Both the total γ-ray distribution, corresponding to some average recoil energy, and a distribution in coincidence with particles scattered into an annular detector symmetric with the incident beam,

TABLE I. Summary of criteria for safe bombarding conditions. R_0 is the radius parameter in Eq. (7), $R = R_0(A_1^{1/3} + A_2^{1/3})$; Δ is the minimum separation between nuclear surfaces in a head-on collision; $E_{\max}$ is the maximum "safe" laboratory bombarding energy for Coulomb excitation of Fe^{56} using these criteria.

	R_0 (F)	Δ	$E_{\max}$ (MeV) O^{16}	S^{32}
de Boer–Eichler (Ref. 14)	1.25	3.0	35.1	80.2
Cline *et al.* (Ref. 6)	1.6	3.0	29.2	66.3
This work	1.6	3.5	28.1	64.0

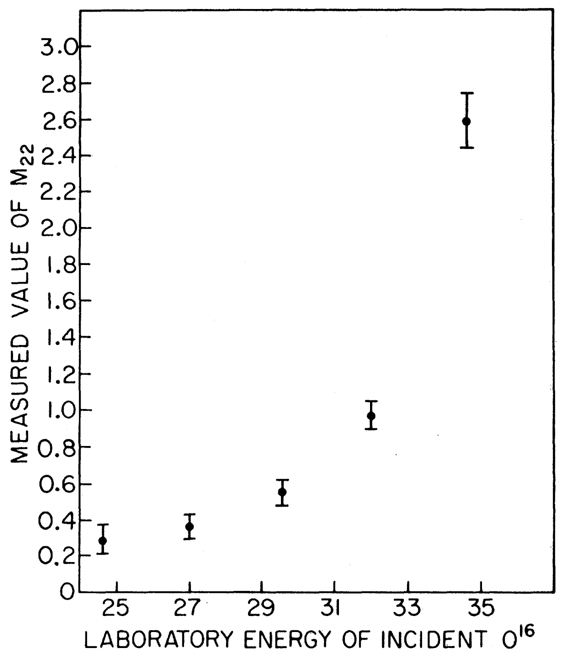

FIG. 8. Extracted values of M_{22} vs incident O^{16} energy assuming pure Coulomb excitation.

corresponding to a higher recoil energy, were taken. The measured distributions are compared with the distributions calculated using the Winther-de Boer program and the coefficients G_2 and G_4 are extracted. The attenuation coefficients measured with respect to the beam are identical to those in Eq. (4) if the perturbing force is randomly oriented.[16]

The G_k were measured using incident 25-, 30-, and 35-MeV O^{16} and 56-MeV S^{32} ions. The G_2 data are plotted versus recoil energy in Fig. 5, as the solid circles and appear to be linear over the range of interest. For purposes of interpolation the G_2 data were fitted to a straight line by least squares. The fit yielded $G_2 = 0.824 - 0.0018E_{\text{recoil}}$ (MeV). The point shown as a solid triangle was taken at 35-MeV incident energy and was not included, since it probably contains nuclear-force effects. The points shown as solid squares are the G_4 measurements. The line drawn through these points is derived from the G_2 line, assuming a randomly oriented static magnetic interaction. This line is $G_4 = 0.584 - 0.0031E_{\text{recoil}}$.

The G_k are interpolated using these straight lines and the crystal correction can be calculated

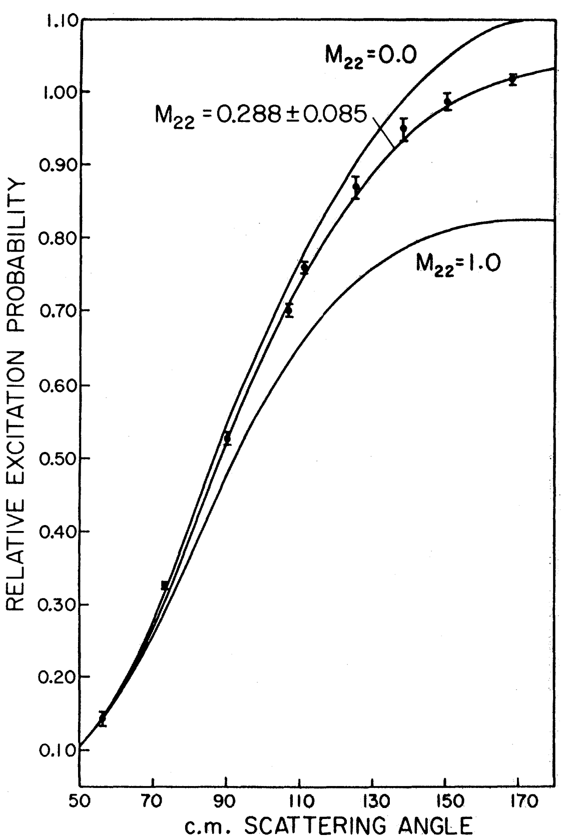

FIG. 9. Relative excitation probability for the 0.847-MeV state of Fe^{56} excited by 25-MeV O^{16} ions.

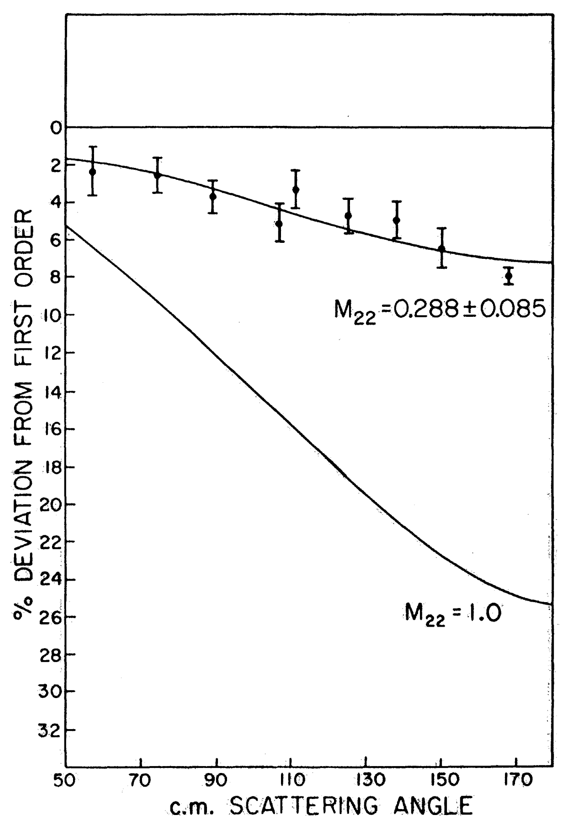

FIG. 10. Percent deviation from first-order excitation probability for the 0.847-MeV state of Fe^{56} excited by 25-MeV O^{16} ions.

using Eq. (6). Figure 6 shows the crystal correction as a function of θ_{Ion} for 25-MeV incident O^{16} and 56-MeV incident S^{32}. The error due to the uncertainties in the measurements of the G_k is 1.3% of $C(\xi, \theta_{Ion})$.

The effect of the relatively high recoil velocity of the target nucleus on the γ-ray angular distribution can be computed. For example, $\beta = V/c \cong 0.015$ for the recoiling target nuclei when 56-MeV S^{32} ions are scattered through 180°. Because of the symmetry of the large γ detector about the z axis in the focal coordinate system, the first-order corrections in β cancel out. The $\beta^2 \cong 2\times10^{-4}$ terms are negligible within the accuracy of these measurements.

The effect of the finite angular resolution of the ion detector on the crystal correction $C(\xi, \theta_{Ion})$ has also been computed and found to be of the order of 0.05%. A decentering error of 1 mm due to a possible γ detector misalignment also introduces corrections of about 0.05% and is considered negligible for the present measurements.

IV. RESULTS

The energy dependence of the reorientation effect was studied using O^{16} ions in an energy range from 22–40 MeV. For these measurements the ratio of the excitation probability $P(163°)/P(45°)$ was observed. This ratio is independent of $B(E2)$ and is proportional to the reorientation effect. The results are shown in Fig. 7. The data have been normalized to the value for the ratio calulated by the Winther–de Boer program for $M_{22} = 0.3$. These data are shown as the solid circles. Similar ratios for the total ion counts at 163° to the total ion counts at 45° normalized to the values predicted by $d\sigma_R/d\Omega$ are shown as the open triangles. For laboratory energies below 27.5 MeV the reorientation effect gives a constant value $M_{22} \sim 0.3$. The first deviation is observed at 28.5 MeV and the deviation becomes massive above 30 MeV. If we attribute this change in the inelastic cross section to the nuclear force, then this nuclear interference effect is observed at a lower energy in the excitation probability than the effect of nuclear interference is observed in the total cross section. Thus the use of the total cross section as an indication of so-called "safe" bombarding energies can lead to significant errors in reorientation measurements. For this case it would give too large a value of M_{22}, i.e., too large a magnitude of $-Q_{22}$. It is convenient to express the distance of closest approach between projectile and target nuclei $(2a)$ in terms of the effective strong interaction radius R_0:

$$2a = R_0(A_1^{1/3} + A_2^{1/3}) + \Delta \text{ (fm)}, \tag{7}$$

where A_1 and A_2 are projectile and target masses and Δ is the "gap" distance.

A summary of safe bombarding conditions is given in Table I, where we have chosen 28 MeV as the maximum "safe" energy. The maximum safe bombarding energies are computed for O^{16} and S^{32} projectiles using the various criteria.

To further investigate the effect of nuclear interference, the angular dependence of the reorientation effect was measured. The incident energies were 25, 27.5, 30, 32.5, and 35 MeV in the laboratory. The results of these measurements are shown in Fig. 8. It is apparent from both this figure and the previous one that erroneous values of M_{22} can be extracted from experiments in which the bombarding conditions are not carefully chosen. Also the influence of the nuclear force produced a similar angular dependence to that of the reorientation effect. Figure 9 shows the results for incident 25-MeV O^{16} projectiles where the data are presented as relative excitation probabilities. Figure 10 shows the same data presented as a percent deviation from first-order excitation probability (or $M_{22} = 0$). Figures 11 and

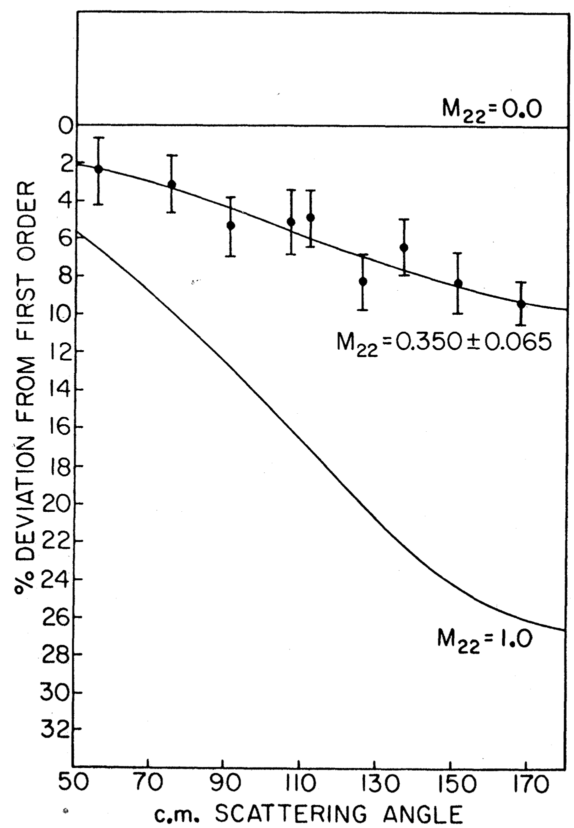

FIG. 11. Percent deviation from first-order excitation probability for the 0.847-MeV state of Fe^{56} excited by 27.5-MeV O^{16} ions.

12 show the similar plots for incident 27.5- and 32.5-MeV projectiles. Even for the 32.5-MeV data, the experimental points correspond quite well to a curve fit using pure Coulomb excitation theory.

We have examined some of the measurements in the literature and find that the criteria $R_0 = 1.6$ fm and $\Delta \geq 3.5$ fm are violated in some of these cases (for example, see Refs. 7 and 10). If the nuclear force contributes significantly it would *increase* the apparent value of a negative quadrupole moment and decrease the apparent value of a positive quadrupole moment of a first excited 2^+ state in an even-even nucleus.

To cross-check the value of Q_{22} obtained at the lower energies we have measured the relative excitation probability $P_{if}(\theta_{\text{Ion}})$ using 56-MeV S^{32} projectiles. The results of these measurements are shown in Fig. 13. Because the raw effect is larger and the gap distance is "safe," the cross-check between the O^{16} and S^{32} data is reassuring.

In order to extract a value of Q_{22} we can use the results of the O^{16} and S^{32} experiments. The values are shown in Table II. If we combine the 25- and 27.5-MeV O^{16} data, we can obtain

TABLE II. Summary of results.

Particle	E_{lab} (MeV)	M_{22} (e b)	Error in M_{22}
O^{16}	25.0	0.288	0.085
O^{16}	27.5	0.350	0.065
S^{32}	56.0	0.308	0.053

$$M_{22} = 0.312 \pm 0.054\,,$$

where a 5% quantum-mechanical correction computed by Pauli and Alder[17] has been applied. Similarly for the S^{32} data we obtain

$$M_{22} = 0.300 \pm 0.053\,,$$

where a 2% quantum-mechanical correction has been applied. Finally, we can extract a combined value

$$M_{22} = 0.306 \pm 0.037$$

and $Q_{22} = -0.23 \pm 0.03$ b for the quadrupole moment of the 0.847-MeV 2^+ state in Fe^{56}. The result is in excellent agreement with a value recently reported by Lesser *et al.*[18]

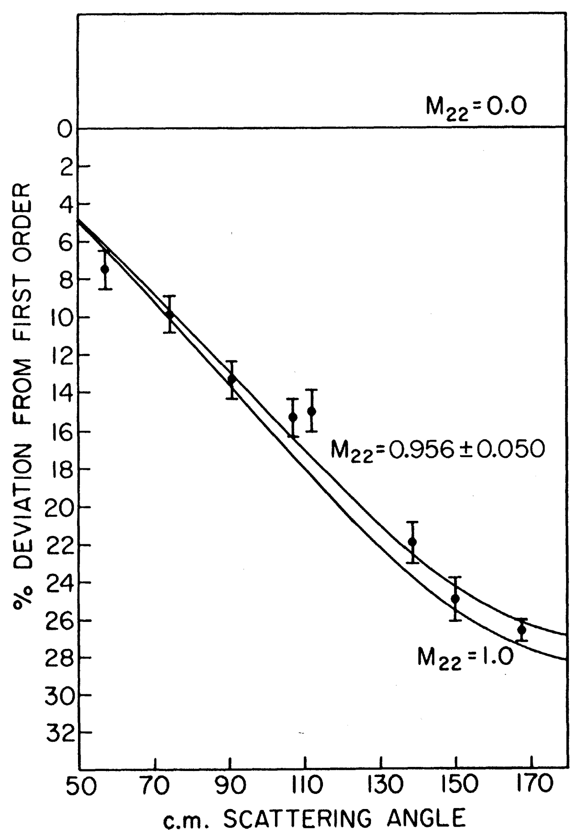

FIG. 12. Percent deviation from first-order excitation probability for the 0.847-MeV state of Fe^{56} excited by 32.5-MeV O^{16} ions.

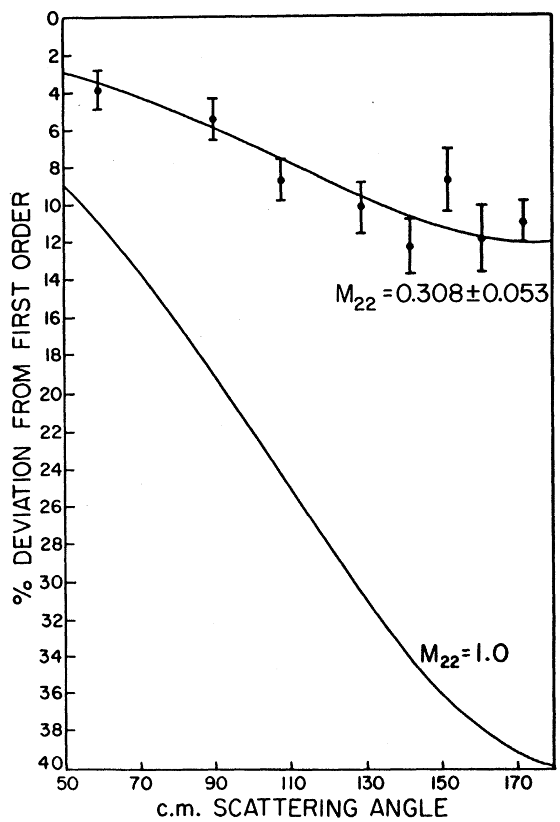

FIG. 13. Percent deviation from first-order excitation probability for the 0.847-MeV state of Fe^{56} excited by 56-MeV S^{32} ions.

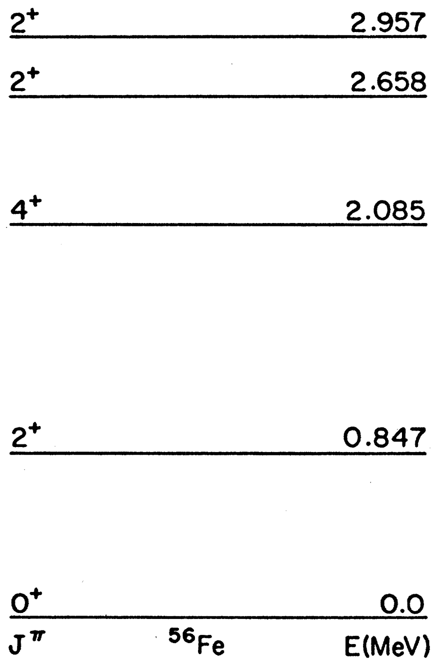

FIG. 14. Low-lying energy levels of Fe^{56}.

V. DISCUSSION

We can compare this result with the predictions of some of the nuclear models. The level diagram of the low-lying states of Fe^{56} is shown in Fig. 14.[19] Following Kumar,[20] if we identify the second 2^+ state as a 2_γ^+ state, then the 2_γ^+, 4^+ level splitting would suggest that the quadrupole moment of the first 2^+ state should be $0.98Q_R$, where Q_R is the rotational limit. For $B(E2)\uparrow = 0.09$ the value of $|Q_R| = 0.276$, which is somewhat larger than the measured value. An earlier measurement gave the result $Q_{22} = -0.345 \pm 0.054$.[8] These values were extracted using 25- and 30-MeV O^{16} data. We can understand the higher result in terms of the present measurement if we include only the 25- and the 30-MeV O^{16} data, as was done in the earlier measurement. The present experiment clearly indicates that the 30-MeV data contain nuclear interference effects and so the extracted quadrupole moment would be too large.

We must leave unanswered the experimental question as to whether the observed deviation from first-order Coulomb excitation includes a contribution due to excitation via the giant dipole resonance because the ratio of giant-dipole interference effect to reorientation effect remains essentially constant for the O^{16} and S^{32} experiments. However, nuclear interference effects dictate stringent criteria for the so-called "safe" bombardment energy because of the relatively slow onset of the nuclear interference with bombarding energy.

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