Rev. Lett. 36, 514 (1976).
[2]J. R. Huizenga, J. R. Birkelund, W. U. Schröder, K. L. Wolf, and V. E. Viola, Jr., Phys. Rev. Lett. 37, 885 (1976).
[3]See J. Galin, J. Phys. (Paris) 37, 83 (1976); or M. Lefort, J. Phys. (Paris) 37, 57 (1976), and references therein.
[4]R. A. Broglia, C. H. Dasso, and A. Winther, Phys. Lett. 61B, 113 (1976).
[5]R. Albrecht, W. Dunnweber, G. Graw, H. Ho, S. G. Steadman, and J. P. Wurm, Phys. Rev. Lett. 34, 1400 (1975).
[6]M. Ishihara, T. Numao, T. Fukuda, K. Tanaka, and I. Inamura, ANL Report No. ANL/PHY 76-2, edited by D. G. Kovar, Proceedings of the Symposium on Macroscopic Features of Heavy Ion Collisions, Argonne, Illinois, 1976 (unpublished), p. 617.
[7]K. Van Bibber, R. Ledoux, S. G. Steadman, F. Videbæk, G. Young, and C. Flaum, Phys. Rev. Lett. 38, 334 (1977).
[8]R. deVries, Phys. Rev. Lett. 30, 666 (1973).
[9]T. E. O. Ericson and V. M. Strutinsky, Nucl. Phys. 8, 284 (1958), and 9, 689 (1959).
[10]E. F. daSilveira, in *Proceedings of the Fourteenth Winter Meeting on Nuclear Physics, Bormio, Italy, 1976* (La Litografia Cislaghi, Rozzano, Italy, 1976).
[11]J. Lang and M. Simonius, Phys. Lett. 46B, 15 (1973).
[12]Calculated assuming classical trajectories with $R = r_0(A_1^{1/3} + A_2^{1/3})$ and $r_0 = 1.35$ fm.
[13]C. F. Tsang, Phys. Scr. 10A, 90 (1974).
[14]P. Braun-Munzinger, T. M. Cormier, and C. K. Gelbke, Phys. Rev. Lett. 37, 1582 (1976).

Observation of the Electrofission of ^{28}Si

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A peak in the yield from the electron-induced fission of ^{28}Si has been observed at an excitation energy of 28.3 MeV, decaying by the channel ^{16}O(g.s.) + ^{12}C^{2+}(4.43 MeV). The angular distribution of the carbon nuclei from this feature follows $(1-\cos^4\theta_{\text{c.m.}})$ indicating an assignment of $J=2$ with a projection along the fission axis of $K=2\hbar$. The observed peak could be due to excitations of the giant quadrupole resonance in the prolate well of ^{28}Si.

In this Letter we report the observation of the fission of ^{28}Si, into ^{12}C and ^{16}O, induced by electrons in the energy range from 23 to 34 MeV. This observation may have important implications for an understanding of the fission process and a possible connection with giant quadrupole resonances. The investigations were carried out at the University of Toronto Electron Linear Accelerator Facility—a conventional pulsed linac with a 10^{-4} duty cycle. For such measurements it is necessary to efficiently detect low yields of carbon and oxygen ions with a large solid angle amidst bursts of scattered electrons, neutrons, protons, etc. To achieve this, thin polycarbonate films were used to record the passage of an ion by the molecular damage created along its track. The particular film used in these experiments was bisphenol-*A* polycarbonate (available as Makrofol, type *KG*, from Bayers Dyestuffs) having an average thickness of 5 μm. Observation of the damage tracks was made possible by chemically etching the foil floating on the surface of sodium hydroxide (7.1 normal at 21°C); we visually counted the holes that broke through to the aluminized surface layer as a function of time.[1] The number of new holes that appear is a peaked function of etching time for monoenergetic ion groups. Below 5.5 MeV for ^{12}C and 8 MeV for ^{16}O there is a one-to-one relation between etching time and energy. The foil is insensitive to α and lighter ionizing radiation at the etching times used.

A consideration of the Q values involved (-16.75 MeV for the decay into the ground states of ^{12}C and ^{16}O) restricts the exit channels that can be observed, below a bombarding energy of 34.0 MeV, to those involving a ^{12}C and an ^{16}O nucleus either both in their ground states or with one in its first excited state (4.4 MeV for ^{12}C or about 6.1 MeV for ^{16}O). The maximum energy of the fragments being observed at a particular electron energy may be unambiguously determined[1] from measurements of the appearance times of the yield when degraded by thin absorbers of various thicknesses. In this way the maximum center-of-mass (c.m.) energy of the ^{12}C fragments being detected with incident electron energies at and below 34 MeV was measured to be 5.2 ± 0.3 MeV. The corresponding maximum oxygen energy must then be 3.9 ± 0.2 MeV which cannot be observed with 5-μm-thick detectors during the etching time used. As a result it was possible to examine tracks due to ^{12}C ions, for $E_{^{12}C}{}^{c.m.} \geq 3.25$ MeV, that were free of ^{16}O tracks because of the known variation in detector response with ion species and energy. The ^{30}Si isotope (3.1% abundance in natural silicon) cannot be involved in the data presented in this Letter due to the Q values involved. The possibility of a contribution from ^{29}Si (4.7%) is discussed later.

Measurements of the ^{12}C yields were carried out at several energies between 23 and 34 MeV with a 57-μg/cm^2 self-supporting Si (natural) target[2] oriented at 45° to the incident electron beam. Oxygen contamination in the target $(2.5\pm0.1)\%$ produces ^{12}C ions from the reaction $^{16}O(e,e'\,^{12}C)\alpha$ that are readily detectable at these bombarding energies. The subtraction of these events ($\leq 12\%$ of the total number of counts) was carried out by a series of measurements to be described in a more detailed publication. The resultant electrofission cross sections measured at 90° to the incident beam are shown in Fig. 1 (solid curve).

An inelastic scattering event can leave the target nucleus with any excitation energy below that of the incident electron, less its rest mass. Consequently, to investigate ^{12}C yields from the various possible decay channels with the limited resolution of the foil detectors it was necessary to vary the electron energy and examine the excitation strength by "differentiating" the electron cross section and converting it into the equivalent cross section for photofission. Using ratios of the total cross sections, in the long-wavelength limit and in the point-nucleus approximation,[3] for the electron process to that for the corresponding photon process (often termed "virtual photon densities"), triple $E2$ difference spectra[4] have been used to obtain the excitation function shown in Fig. 1 (dashed curve). The points shown represent integrals of the equivalent photon cross section over regions of excitation energy specified by the horizontal bars. If either electric dipole excitation or a mixture of dipole with quadrupole absorption is assumed, the shape of the (dashed) yield curve shown in Fig. 1 remains the same while the cross sections increase by at most 10%.

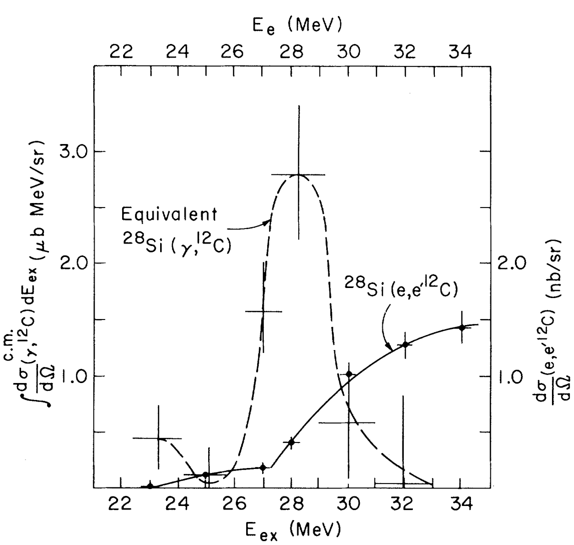

FIG. 1. The differential cross section measured at $\theta_{lab}=90°$ for $^{28}Si(e,e'\,^{12}C)$, $E_{^{12}C}{}^{c.m.}\geq 3.25$ MeV (solid line), is shown here with the scale on the right-hand side of the figure. The horizontal error bars reflect the systematic uncertainties in the electron beam energy with the scale at the top of the figure. The equivalent photon-induced cross section is also shown (dashed line) with its scale on the left. (The curves are merely drawn to guide the eye.)

The yield above 25 MeV must be due to decays leaving one of the fragments in its first excited state because of the measured maximum ^{12}C energy discussed above. At the peak excitation energy of 28.3 MeV the decay channel leaving the ^{16}O nucleus in an excited state would produce 3.1-MeV ^{12}C nuclei which are not detectable in the etching times to which this analysis has been restricted. The detector response shows a preponderance of ions with at least 4 MeV of energy. These considerations demonstrate that the electrofission yield centered around 28.3 MeV excitation proceeds with a $\geq 90\%$ branch via the decay channel

$$^{28}Si \rightarrow {}^{12}C^{2+}(4.43\text{ MeV}) + {}^{16}O. \qquad (1)$$

The $(\gamma,2n)$ threshold in silicon is at 30.5 MeV and thus does not affect the falloff of the observed yield that occurs above 29 MeV in excitation. The decay channel (1) gives a maximum of 3.4-MeV ^{12}C nuclei at 27.1 MeV of excitation which are detected with better than 90% efficiency for the restricted etching times used here, although longer times would be necessary to investigate the yield much below this. This leads to the interpretation of the feature at 28.3 MeV as a resonance or cluster of resonances with a spread of about 2.5 MeV and a total energy-integrated equivalent photon-induced cross section of 45 $\pm$ 9 μb MeV. The Coulomb barrier for the ^{16}O plus ^{12}C system is at a center-of-mass energy of about 8 MeV,[5] so that the observed decays occur

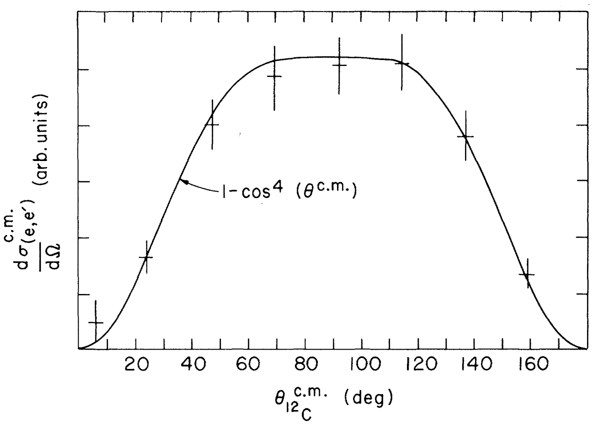

FIG. 2. The center-of-mass angular distribution of the ^{12}C nuclei with $E_{^{12}C}{}^{c.m.} \geqslant 3.25$ MeV from the decay ^{28}Si$(e,e'\,^{16}$O$)^{12}$C^{2+} (4.43 MeV) is shown here for an electron bombarding of 34.0 MeV.

near the top of this barrier. The dropoff in yield at the low-excitation-energy end of Fig. 1 could thus be influenced in part by barrier attenuation effects.

Angular distributions were measured simultaneously with the yield measurements described above. The effects of the kinematic difference between center-of-mass and laboratory frames were removed by experiments using appropriate thin carbon absorbers at each angle to reduce the carbon ion energies to a common value. A resultant angular distribution, corrected for the solid-angle differences between frames as well as for ^{16}O$(e,e'\,^{12}$C$)\alpha$ contamination, is shown in Fig. 2.[6]

Electroexcitation in which the final electron energy is near zero proceeds via the exchange of a single virtual photon traveling parallel to the beam direction and is equivalent (with small correction factors) to real photoabsorption. The excitation then aligns the target nucleus with a spin projection of $\pm 1\hbar$ along the beam axis. In considering nuclear deformations leading to fission it is reasonable to consider cases where the saddle-point configuration is cylindrically symmetric about the fission axis and has a definite value for the projection of the total angular momentum along this direction. If the yield shown in Fig. 1 is assumed to proceed by $E2$ absorption to a state having a definite total angular momentum projection along the scission axis of $K = 2\hbar$ then the resultant angular distribution is[7]

$$W(\theta_{c.m.}) \propto 1 - \cos^4\theta_{c.m.} . \qquad (2)$$

This is the solid curve drawn through the points in Fig. 2. It should be noted that although the expression in (2) can also be written as $\sin^2\theta + \frac{1}{4} \times \sin^2 2\theta$, we regard the possibility of having a constant ratio for $E1$ and $E2$ absorption and for the associated decays over the entire feature of Fig. 1 as being highly unlikely. $M2$ absorption would yield the same angular dependence but is expected to be much less than $E2$ for collective excitations.[8] The ^{29}Si contribution (4.7% abundant) is as yet unknown. However, the steeply varying angular distribution indicates a significant $P_4(\cos\theta)$ component while the distributions for a J^π of $\frac{5}{2}^+$ and any single K value are quite unlike that of Fig. 2. We therefore attribute the observed events to the fission of ^{28}Si until detailed studies of ^{29}Si are possible.

A ^{28}Si nucleus can be considered to be an oblate spheroid in its low-lying states.[9] Since the excitation is a result of a one-body operator, the excited nucleus, at least initially, must be essentially identical to the ground state—i.e., again oblate. Assuming the subsequent collective deformation and scission to be adiabatic, there must be a continuous connection between the wave function of the fragments and that of the compound nucleus in its initial excited configuration. However, in a simple molecular-oscillator model[10] the Pauli principle forbids the production of ^{12}C and ^{16}O fragments from the oblate shape of ^{28}Si. There is only a path from the prolate shape. An inspection of single-nucleon two-centered shell-model states gives the same result. Constrained Hartree-Fock calculations[11] show that the level spectrum of ^{28}Si below 8 MeV is consistent with the coexistence of both prolate and oblate intrinsic shapes, the oblate well being deeper and associated with the ground state. The predicted spherical barrier between the oblate and prolate wells is about 29 MeV suggesting overlap between states in the two wells near this energy. This is close to the energy of the peak shown in Fig. 1.

Knöpfle *et al.*[12] have recently reported a peak at 20 MeV, with a full width at half-maximum of about 5 MeV, in the inelastic scattering of 155-MeV α particles by ^{28}Si that could be quadrupole in nature.[13] These measurements were sensitive to states in the oblate well.[14] The feature they observed could be associated with the giant quadrupole resonance (GQR) of the oblate shape of ^{28}Si. If the same frequency (20.0 ± 2.5 MeV/$\hbar$) for collective quadrupole oscillation is assumed for both wells, then the electrofission yield shown in

Fig. 1 could be associated with part of the GQR of the prolate shape of ^{28}Si since the energy difference between the two wells is about 6.7 MeV.[11,15]

The definite value for the projection of the total angular momentum along the fission axis may be a characteristic of the saddle shape alone, the barrier being effectively lowest for a projection of $2\hbar$. This is not inconsistent with a predicted splitting of the GQR due to vibrational degrees of freedom.[16,17] The absence of a prominent $K=0$ component, which would lie lower in energy than the $K=2$ component in a prolate nucleus, could at least partly be due to the oblate-prolate barrier.

The contribution of the measured yield to the quadrupole energy-weighted sum rule is $0.16\langle\Gamma_{^{12}\text{C}}/\Gamma\rangle^{-1}$ (%). Here Γ and $\Gamma_{^{12}\text{C}}$ are the full and partial ^{12}C widths, respectively. Although this is apparently quite small, it is difficult to estimate the penetrability factor for transitions between the two wells since little attention has been paid to the the barrier in theoretical calculations of ^{28}Si. In addition, branching ratios for decays into other channels are as yet unknown.

In summary, the peaked ^{12}C yield with its rapid falloff above 29-MeV excitation as well as the ^{12}C angular distributions could be accounted for by excitations in the oblate well, via inelastic electron scattering, to states that have appreciable overlap with at least part of the GQR of the prolate shape due to the nature of the barrier between the two wells. This suggests the possibility of a connection between the modes of collective motion involved in the GQR and instabilities leading to the fission of ^{28}Si. Such a possibility may be worth a detailed study in silicon and among neighboring light nuclei.

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[1]R. Fleischer, P. Price, and R. Walker, *Nuclear Tracks in Solids* (Univ. of California Press, Berkeley, 1975), pp. 136–137; Figure 3–13 shows a calibration curve for 6-μm-thick Makrofol.

[2]A. Sandorfi *et al.*, Nucl. Instrum. Methods 136, 395 (1976).

[3]G. Bishop, in *Nuclear Structure and E & M Interactions, Scottish Universities Summer School, Edinburgh, Scotland, 1964*, edited by N. MacDonald (Oliver and Boyd, Edinburgh, Scotland, 1964).

[4]B. Cook, Nucl. Instrum. Methods 24, 256 (1963).

[5]H. Frölich *et al.*, Phys. Lett. 64B, 408 (1976).

[6]Previous electrofission experiments had been restricted to angles greater than 80° to the incident electron beam direction. [A preliminary report on ^{24}Mg(e,e' ^{12}C)^{12}C is given by A. Chung *et al.*, Phys. Lett. 53B, 244 (1974)]. The corrections to the laboratory angular distributions discussed above have provided reliable data at angles $\theta_{^{12}\text{C}} \geq 18°$. The effects of large radiation doses on the response of the foil detectors are apparent at more forward angles and are still being investigated.

[7]R. Vandenbosch and T. Huizenga, *Nuclear Fission* (Academic, New York, 1973), p. 115.

[8]L. Schiff, Phys. Rev. 96, 765 (1954).

[9]H. C. Lee, J. Phys. Jpn. 34, 445 (1973).

[10]M. Harvey, in *Proceedings of the Second International Conference on Clustering Phenomenon in Nuclei*, College Park, Maryland, 1975, edited by D. A. Goldberg, J. B. Marion, and S. J. Wallace, ERDA Report No. ORO-4865-26 (National Technical Information Service, Springfield, Va., 1975).

[11]S. Das Gupta and M. Harvey, Ncul. Phys. A94, 602 (1967); B. Castel and J. Svenne, Nucl. Phys. A127, 141 (1969).

[12]K. Knöpfle *et al.*, Phys. Lett. 64B, 263 (1976).

[13]These measurements were restricted to excitation energies below 24 MeV due to α background from the unbound mass-5 system. See, for example, A. Kiss *et al.*, Phys. Rev. Lett. 37, 1188 (1976). Measurements with ~200 MeV α's would be necessary in order to observe the region near 28 MeV.

[14]The sensitivity to oblate components of states in the prolate well is limited by the barrier between wells.

[15]P. Strehl, Z. Phys. 234, 416 (1970). Strong monopole excitation of the 4.98-MeV state in ^{28}Si following inelastic electron scattering is observed in contrast to a very weak excitation (10:1) of the 6.69-MeV state.

[16]R. Ligensa and W. Greiner, Nucl. Phys. A92, 673 (1967).

[17]N. Auerbach and A. Yeverechyahu, Phys. Lett. 62B, 143 (1976).