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Resonance fluorescence from the 7.08-MeV state in ^{208}Pb

W. Scholz and H. Bakhru
Department of Physics, State University of New York at Albany, Albany, New York 12222

R. Collé* and Angela Li-Scholz†
Department of Chemistry, Rensselaer Polytechnic Institute,‡ Troy, New York 12181

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The Doppler-broadened 7.12-MeV transition from the $^{19}F(p,\alpha\gamma)^{16}O$ reaction has been used to fluoresce resonantly a level at 7.084 ± 0.002 MeV in ^{208}Pb. A spin value of $J = 1$ has been assigned by measuring the intensity of the scattered radiation at average scattering angles of 90 and 130°. From a study of the intensity growth of the scattered radiation with increasing scatterer thickness (production experiment), the following level parameters were extracted: integrated scattering cross section $\int \sigma_s \, dE = 2.07 \pm 0.18$ MeV mb, maximum absorption cross section $\sigma_A^{\max} = 85^{+36}_{-31}$ b, total level width $\Gamma = 26^{+35}_{-12}$ eV, and partial width for the ground-state transition $\Gamma_0 = 16^{+6}_{-4}$ eV.

[NUCLEAR REACTIONS $^{208}Pb(\gamma,\gamma')$, $E \approx 7$ MeV; measured $\sigma(E_\gamma;\theta)$. ^{208}Pb deduced level Γ, Γ_0, $\sigma_A^{\max}$, J. Natural Pb targets, resonance-fluorescence production experiment.]

I. INTRODUCTION

During the past few years, a great deal of information has been accumulated on the doubly magic nucleus ^{208}Pb and other nearby nuclei.[1] Much of the work has been prompted by the success of various nuclear models such as the particle-hole model,[2,3] the pairing-vibration model,[4,5] and the particle-core weak-coupling model.[6-8]

Despite the considerable amount of experimental data available on ^{208}Pb, little is known about the radiative decay properties of low-spin states below the neutron-capture threshold. Nuclear resonance fluorescence has been observed from a number of states.[1,9-12] Ground-state branching fractions have been measured for 10 states between 5.08 and 7.09 MeV excitation energy formed via inelastic proton scattering on analog resonances.[13] Finally, the γ decay of selected levels below 7.3 MeV has been investigated with the $^{207}Pb(d,p\gamma)^{208}Pb$ reaction.[14]

In the present studies, the Doppler-broadened 7.12-MeV transition from the $^{19}F(p,\alpha\gamma)^{16}O$ reaction was used to resonantly fluoresce a level at 7.084 MeV in ^{208}Pb. Resonance fluorescence in this energy region had been observed in several previous experiments. The experiment of Reibel and Mann[15] was performed under conditions similar to the present work, albeit using a NaI(Tl) detector. In the studies of Axel *et al.*[9] a variable-energy photon beam of about 1% resolution was used. In this latter experiment, strong resonance scattering from a state near 7.03 MeV in ^{208}Pb was observed. However, the nucleus ^{206}Pb also gives rise to resonance scattering in this energy region. Furthermore, at least two states within 20 keV of each other appear to exhibit resonance fluorescence in the vicinity of 7.07 MeV in ^{208}Pb (see Ref. 10 and additional results quoted in Ref. 14). Recently, in an experiment similar to ours Swann[12] has demonstrated that the resonance scattering from natural lead in this energy region is dominated by two states at 7.071 and 7.091 MeV in ^{208}Pb. Their level widths have been calculated assuming 100% ground-state branching.[12] In our experiment using a natural lead target only the upper level overlapped sufficiently with the spectrum of the primary radiation to be excited. Level parameters for this state were obtained from a detailed analysis of the scattered photon yield from natural lead targets of varying thickness (production experiment). Additionally, the spin of this state was determined by measuring the intensity of the scattered radiation at average scattering angles of 90 and 130°. The analysis of the production experiment was performed with the assumption that the level observed belongs to either ^{206}Pb or ^{208}Pb. The isotope ^{207}Pb has its neutron threshold at 6.74 MeV[1] and was not considered. Level parameters obtained for the case of ^{206}Pb were found to be at variance with theoretical limits and published quasielastic photon scattering cross sections.[9,15] Preliminary results have been reported elsewhere.[16]

II. EXPERIMENTAL

The primary photon beam was produced with the $^{19}F(p,\alpha\gamma)^{16}O$ reaction. A thick CaF_2 pressed pellet was bombarded with 2.1-MeV protons from the Dynamitron accelerator at the State University of New York at Albany. The average proton current was 20–40 μA. Under these conditions, the ground-state transitions from the 6.13-, 6.92-, and 7.12-MeV states in ^{16}O are observed with relative intensities of approximately 3 : 2 : 6. The latter two states have lifetimes of the order of 10^{-13} sec and consequently show extensive Doppler broadening. Specifically, the 7.119-MeV transition[17] has a width of 127 keV and subtends an energy range from 7.079 to 7.206 MeV at 0° with respect to the proton beam.

The scatterers were 10-cm×10-cm Pb metal sheets of natural isotopic composition. Five scatterers, varying in thickness from 0.18 to 5.15 cm, were used for the production measurement. As shown in Fig. 1, they were positioned at 0° with respect to the incident proton beam at a distance of 40 cm from the CaF_2 target. The scattered radiation was detected in a 21-cm^3 coaxial Ge(Li) detector positioned 10 cm from the center of the scatterers at 90° with respect to the incident photon direction. The scatterers were oriented at 45° with respect to the incident beam. The Ge(Li) detector was shielded from the primary photon source by 30 cm of lead. A 0.46-cm-thick lead absorber was used in front of the detector to filter out electrons and low-energy γ rays produced in the scatterers. Amplified pulses from the Ge(Li) detector were analyzed with a 4096-channel analog-to-digital converter interfaced to an on-line PDP-15 computer.

A 7.6-cm×7.6-cm NaI(Tl) scintillator, placed 330 cm from the target at 90° with respect to the incident proton beam, was used as a monitor detector to normalize individual runs to each other. In order to avoid high count rates in the monitor, a 5-cm-thick lead absorber was used to shield the crystal from the photon source. The detection efficiencies of the monitor counter and the Ge(Li) detector were determined relative to each other by placing the latter into the primary photon beam 90 and 150 cm from the target at 0° with respect to the incident proton beam [Fig. 2(a)]. By subsequently normalizing the Ge(Li) detector spectra [Figs. 2(a) and 2(b)] to the monitor count rates, knowledge of absolute values for the primary and scattered photon intensities was obviated. Apart from a small correction which will be described later, the efficiency of the Ge(Li) detector was eliminated from the analysis of the present experiment. A background spectrum without a scatterer in place was also measured [Fig. 2(c)] to ascertain that the 7.08-MeV γ ray originated in the lead scatterer.

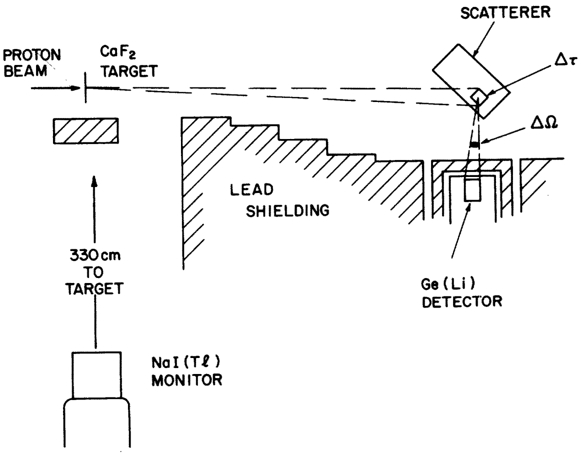

FIG. 1. Geometry used for the scattering experiments.

The setup for the angular distribution experiment was similar. Two measurements, at average scattering angles of 90 and 130°, respectively, were taken using a 0.92-cm-thick scatterer. In the first instance the distance from target to scatterer was 47 cm and from scatterer to detector front 14.4 cm. The corresponding values for the second case were 63 and 21.9 cm, respectively. A 49-cm^3 coaxial Ge(Li) detector was used for these measurements.

III. ANALYSIS

In resonance scattering experiments, the distinction is often made between self-absorption measurements and production measurements. In the former, the attenuation in the number of scattered photons is determined as a function of the thickness of absorber placed in the incident beam while in the latter, the growth of the number of scattered photons is observed as the thickness of the scatterer is increased. Although the formalisms for the analysis of both types of measurements are available in the literature,[18–21] the computational requirements remain nontrivial. The analysis of the present production measurement was performed following the approach given by Schmid and Scholz.[20]

A volume element $\Delta\tau$ at a distance r from the photon source gives the following contribution to the number of photons scattered into the detector (Fig. 1):

$$\Delta I_s = \frac{N\Delta\tau\Delta\Omega}{r^2} P(\theta) \frac{dI}{dE} \exp[-\mu_{\rm el}(x_1 + x_2)] W(c, t) \int \sigma_s dE \,. \tag{1}$$

In this equation, N is the number of scattering nuclei per cm^3, $\Delta\Omega$ the solid angle of the detector with reference to $\Delta\tau$, $P(\theta)$ describes the angular dependence appropriate to the multipolarity of the

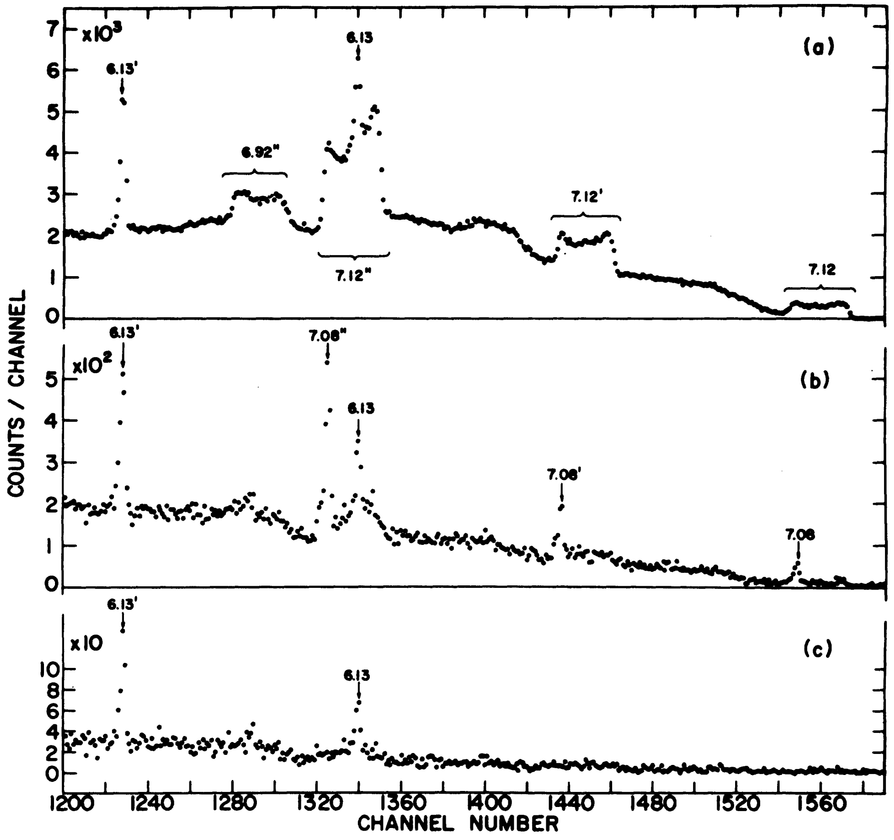

FIG. 2. Photon spectra measured with the Ge(Li) detector: (a) direct spectrum 90 cm from the target at 0° with respect to the incident proton beam showing the Doppler-broadened 6.92- and 7.12-MeV transitions and the narrow 6.13-MeV line; (b) scattered spectrum obtained by summation of the spectra from all scatterers; (c) background measured without scatterer showing incompletely shielded 6.13-MeV line from the target.

γ ray in question, $\int \sigma_s dE$ is the integrated scattering cross section, and dI/dE is the number of primary photons of energy E per energy interval dE per unit solid angle at the scatterer position. For level widths small compared with the width of the incident photon spectrum, dI/dE can be considered constant. The exponential term is included to account for electronic absorption of the incident and scattered radiation, where μ_{el} is the electronic absorption coefficient, and x_1 and x_2 are the photon path lengths in the scatterer before and after the resonant scattering, respectively. The function $W(c, t)$ is a universal integral defined in Refs. 19 and 20, which involves the Breit-Wigner single-level formula modified by folding in Doppler broadening due to the thermal motion of the scattering nuclei. It basically expresses only the fact that γ rays are reasonantly scattered and absorbed in traversing the target. The individual character of the particular target material enters through the values of the parameters $c = N\sigma_A^{max} x_1$ and $t = (\delta/\Gamma)^2$, where σ_A^{max} is the maximum absorption cross section and Γ and δ are the level and the Doppler width, respectively. This function was computed to four significant places for an appropriate range of values for c and t.

By substituting the angular dependence for a dipole transition $P(\theta) = (3/16\pi)(1 + \cos^2\theta)$, as justified in the following section, one obtains from a numerical integration of Eq. (1)

$$\sum \Delta I_s/(dI/dE) = \alpha_i(\sigma_A^{max}, t)N \int \sigma_s dE\,. \qquad (2)$$

From the measurement of $\sum \Delta I_s/(dI/dE)$ and the computed values of α_i, the integrated scattering cross section can be extracted.

The quantities α_i for the five scatterers were computed for six values of σ_A^{max} between 50 and 150 b and for six values of t between 0 and 1. The value for N used in the calculation was obtained assuming, respectively, a 23.6 and 52.3% isotopic content of ^{206}Pb and ^{208}Pb in natural lead. Numbers given in the literature for the electronic absorption coefficient of lead differ from each other by as much as 10%. A value of $\mu_{el} = 0.508\ \mathrm{cm}^{-1}$, taken from an interpolation of the data in Ref. 22, was used in the analysis. The influence on α_i due to a variation in μ_{el} was also investigated. It was found that a 5% change in μ_{el} results in a 2% change in α_i, and hence in $\int \sigma_s dE$. The intensities of the scattered and primary photons need to be determined only as the ratio $\sum \Delta I_s/(dI/dE)$. The ratio of intensities is simply derivable from the ratio of normalized count rates provided the detection efficiency is strictly proportional to the inverse square of the source distance. However, due to the very different geometries under which the primary and scattered photons were measured, corrections have to be made which account for the relative variation of the efficiency with source distance and angle of incidence. Calculations of the intrinsic detection efficiency using the total absorption coefficient for Ge at 7 MeV showed that the intrinsic detection efficiency for radiation originating from various points in the scatterer was 23 to 10% lower than that for the primary radiation at the 150-cm axial geometry. These calculations were used to make a point-by-point efficiency correction over all volume elements in the numerical computation of α_i. A calculation without the inclusion of this correction was also performed to establish its effect on the results of the analysis.

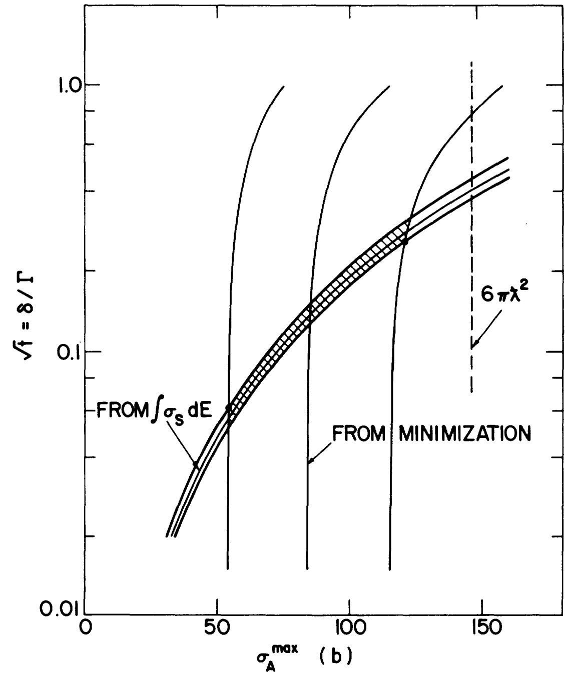

FIG. 3. Maximum absorption cross section vs $\sqrt{t} = \delta/\Gamma$. The shaded region contains the values of σ_A^{max} and $\sqrt{t}$ that are compatible with the results of the production experiment. For details see text.

The convergence of the numerical integration was checked by varying the size of the volume element. For the final analysis, a volume element of 1 cm wide × 1 cm high × 0.0233 cm thick was chosen. Doubling the thickness of this element caused changes in α_i of less than 1 part in 10^4. Thus, computational uncertainties on the α_i need not be considered.

Optimum values of σ_A^{max} can be found as a function of t by minimizing the dispersion in the integrated cross section obtained from Eq. (2) for the five different scatterers. The dependence of σ_A^{max} on t obtained in this fashion is shown in Fig. 3 for the case of ^{208}Pb. The value of $\int \sigma_s dE$ obtained at the optimum value of σ_A^{max} is essentially independent of t, ranging only from 2.05 to 2.07 MeV mb. An 8.6% error has been assigned to the integrated scattering cross section, which is the quadratic sum of contributions from counting statistics (4.4%), measurement of the primary intensity dI/dE (5%), uncertainty of intrinsic efficiency correction factor (5%), and a consequence of a 5% uncertainty in the electronic absorption of lead (2%). This error can be used to obtain an estimate for the uncertainty on σ_A^{max}. Values of σ_A^{max} leading to an integrated scattering cross section consistent with the above error limits are indicated by the vertical band in Fig. 3, the left- and right-hand curve corresponding to the lower and upper limit of $\int \sigma_s dE$, respectively. An additional restriction on σ_A^{max} is obtained from the Breit-Wigner expression. Specifically, for a dipole transition in an even-even nucleus

$$\sigma_A^{max} = 6\pi\bar{\lambda}^2(\Gamma_0/\Gamma), \tag{3}$$

with $\bar{\lambda} = \hbar c/E_r$, where E_r is the resonance energy of the nuclear state and Γ_0 is the partial level width for decay to the ground state. The limiting value of $6\pi\bar{\lambda}^2$ is also shown in Fig. 3.

A second relationship between σ_A^{max} and t can be obtained via the level width Γ. Using the definition of t and combining Eq. (3) with the identity

$$\int \sigma_s dE = \tfrac{1}{2}\pi\sigma_A^{max}\Gamma_0, \tag{4}$$

one obtains for a dipole transition

$$\tfrac{1}{2}\pi\delta/\sqrt{t} = \tfrac{1}{2}\pi\Gamma = 6\pi\bar{\lambda}^2 \int \sigma_s dE/(\sigma_A^{max})^2. \tag{5}$$

This relationship is also depicted in Fig. 3, where the lower curve corresponds to the upper limit on $\int \sigma_s dE$ and vice versa. A Doppler width of $\delta = 3.67$ eV was used which corresponds to a room temperature of 300K. Since the Debye temperature of Pb is only 94.5K,[23] no effective temperature correction was necessary.[24] The shaded area in Fig. 3 represents the region of overlap of the two bands of $\sigma_A^{\max}$ and t values consistent with the error limits on $\int \sigma_s dE$. At the intersection of the shaded band with the line of minimum dispersion, the integrated scattering cross section has a value of 2.07 MeV mb. Due to the correlated nature of the errors, the appropriate extreme values for $\sigma_A^{\max}$ and t are those represented by the dots in Fig. 3.

IV. RESULTS AND DISCUSSION

From the spectrum of the scattered radiation, the excitation energy of the resonantly fluorescing state was determined as $E_r = 7.084 \pm 0.002$ MeV. The energy of the nearby background line resulting from the (6.130 66 ± 0.000 18)-MeV state[17] in ^{16}O was used as a reference. As discussed in the next paragraph, the possibility that the level in question belongs to ^{206}Pb can be excluded. For the case of ^{208}Pb, the level parameters obtained from the analysis described in the previous section are as follows: the integrated scattering cross section, $\int \sigma_s dE = 2.07 \pm 0.18$ MeV mb; the maximum absorption cross section, $\sigma_A^{\max} = 85^{+36}_{-31}$ b; and the ratio of Doppler width to level width, $\delta/\Gamma = \sqrt{t} = 0.14^{+0.12}_{-0.08}$ (Fig. 3). Using a value of $\delta = 3.67$ eV for the Doppler width, the total level width becomes $\Gamma = 26^{+35}_{-12}$ eV. By application of Eq. (3) the branching ratio for the ground-state transition can be determined from the maximum absorption cross section as $\Gamma_0/\Gamma = 0.58^{+0.26}_{-0.20}$. The partial width to the ground state is obtained by inserting the values for the integrated scattering cross section and the maximum absorption cross section with their correlated errors into Eq. (4). The resultant value of $\Gamma_0 = 16^{+6}_{-4}$ eV is somewhat larger than that obtained in a preliminary analysis where $\sigma_A^{\max} = 6\pi\lambdabar^2 = 146$ b had been assumed.[16]

The analysis performed with the assumption that the observed resonance scattering is due to a level in ^{206}Pb yielded the following results: the integrated scattering cross section, $\int \sigma_s dE = 4.65 \pm 0.42$ MeV mb; the maximum absorption cross section, $\sigma_A^{\max} = 200^{+55}_{-50}$ b; and the ratio of Doppler width to level width $\delta/\Gamma = \sqrt{t} = 0.34^{+0.16}_{-0.13}$. This value for the integrated scattering cross section would be at variance with published quasielastic photon scattering cross sections for ^{206}Pb in the vicinity of 7 MeV[9,15] which do not allow for an integrated scattering cross section much larger than about 1.0-1.6 MeV mb if the energy spread of the incident photon beam is taken into consideration. In addition, the value of the maximum absorption cross section arrived at in the analysis appears to exceed the theoretical maximum value of 146 b. Thus, the possibility that the observed resonance scattering arises from a state in ^{206}Pb can be excluded.

The results of the analysis given above were obtained using the angular dependence for dipole radiation. This was verified in an independent angular distribution measurement. At average scattering angles of 90 and 130° an intensity ratio of $I(90°)/I(130°) = 2.27 \pm 0.46$ was observed with the geometries described in Sec. II. Intensity ratios calculated for the two geometries using $\sigma_A^{\max} = 85$ b and $t = 0$ were 2.82, 7.79, and 0.93 for dipole, quadrupole, and octupole radiation, respectively, thus allowing for a dipole transition only.

The observed ground-state radiative width of $\Gamma_0 = 16^{+6}_{-4}$ eV compares well with the value of 17 ± 2 eV given by Swann[12] for a $J = 1$ state at 7091 ± 3 keV in ^{208}Pb and with the value of 15 eV obtained by Khan and Knowles (see Ref. 10 and further results quoted in Ref. 14) for a state at 7074 ± 3 keV. In the latter two experiments a second state with a ground-state width of, respectively, 31 eV[12] and 15 eV[10,14] was also observed at about 20 keV lower energy. The two states were presumably not resolved in the photon scattering experiment on ^{208}Pb using a variable energy photon beam of about 1% resolution which yielded a ground-state radiative width of about 30 eV.[9] In our experiment, which had a detector resolution of full width at half maximum (FWHM) of about 12 keV, only the upper level overlapped sufficiently with the spectrum of the primary radiation to be excited.

The observed partial width to the ground state corresponds to 0.019 and 2.1 Weisskopf units for an $E1$ or $M1$ transition, respectively.[25] Although the transition could conceivably be $M1$, such an assignment is unlikely in view of the distribution of $M1$ transition strengths observed in heavy nuclei.[25] Thus, it appears that the 7.083-MeV state has most likely spin and parity $J^\pi = 1^-$ and is associated with minor constituents of the giant dipole resonance. Fragments of the giant dipole strengths have been predicted at around 7 MeV by the particle-hole model.[2,3]

The comparatively small value found for the branching ratio to the ground state is rather surprising in view of the fact that no inelastic transitions could be found. However, it is in agreement with the results of a $(p, p'\gamma)$ experiment on ^{208}Pb, where a probable 1^- state at 7.09 MeV with a 50 ± 4% ground-state branch was observed.[13] An upper limit of about 10% can be put for any cascading branch in which a high-energy γ ray is emitted. The result that no such γ rays were seen implies that either the missing transition strength is very fragmented or that low-energy transitions feed 0^+ states which then decay mainly by an $E0$ mode. Low-energy transitions could have been missed because of the presence of an intense bremsstrahlung background. The predominance of an $E0$ mode in the decay of a 0^+ state has been reported for the 1.17-MeV state in ^{206}Pb (Ref. 26). Such a $0^+ \to 0^+$ transition would, of course, have been undetected in the present γ-ray measurement.

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*Present address: Department of Chemistry, University of Maryland, College Park, Maryland 20742.

†Present address: State University of New York, Empire State College, Albany, New York 12206.

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