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ELECTROEXCITATION OF THE LOW-LYING STATES OF O^{16} †

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Measurements are reported of form factors for the electroexcitation of the 0^+ (6.052-MeV), 3^- (6.131-MeV), 2^+ (6.916-MeV), and 1^- (7.115-MeV) states of O^{16}, in the momentum-transfer region 0.5 to 1.0 fm^{-1}. The data are compared with the predictions of various particle-hole shell models and a two-component phenomenological model.

In this Letter, we wish to report measurements of the form factors for electroexcitation of the 0^+ (6.052-MeV), 3^- (6.131-MeV), 2^+ (6.916-MeV), and 1^- (7.115-MeV) states of O^{16}, in the momentum-transfer region 0.5 to 1.0 fm^{-1}. The experiment was carried out at the electron linear accelerator facility of the National Bureau of Standards.

An oxygen target was provided by a 35-mg/cm^2 wafer of beryllium oxide, oriented for transmission scattering. Scattered electrons were detected by a 20-detector array of lithium-drifted silicon semiconductors[1] ($1\times1.25\times60$ mm) positioned along the focal plane of a 30-in. radius of curvature, 169.8° double focusing ($n=\frac{1}{2}$) spectrometer.[2] Background events were minimized by a triple coincidence requirement between the semiconductors and two large plastic scintillators situated behind the array. Two scattering angles were employed, 110° and 145°, and the incident beam energy was varied between 51 and 105 MeV. Average beam current was 1-3 μA, and accumulated charge was continuously monitored by a Faraday cup. The overall resolution was about 0.10%. The 2^+1^- doublet was completely resolved at all energies, and the 0^+3^- doublet was resolved at the lower energies. The 0^+ and 3^- states were not resolved at the higher energies and line-shape fitting to the spectra was used to separate them.

The broad $\frac{7}{2}^-$ (6.66-MeV) state in beryllium makes a non-negligible contribution to the spectrum. Therefore, data were also taken on a beryllium target (70 mg/cm^2), and the normalized spectra were subtracted from the BeO spectra. The remaining background underlying the doublets, mostly radiation tail from elastic scattering, was determined by linear interpolation from the spectra on either side of the doublets, in conjunction with a line-shape-fitting procedure which yielded the shapes of the peaks, their radiation tails, and their areas.

Figure 1 illustrates two spectra, the 0^+3^- doublet at 59.7-MeV indicent energy, and the 2^+1^- doublet at 105 MeV. In both cases, the oxygen elastic radiation tail and other backgrounds have been removed. The error bars are the standard deviations due to counting statistics in each bin. The nonstatistical appearance of the spectra originates from the procedure for sorting data into energy bins; one counter contributes to several bins.

The squares of the inelastic form factors [the ratio of the inelastic cross section to the Mott cross section ($Z=8$)] for the 3^- (6.131-MeV) and 1^- (7.115-MeV) levels are displayed in Fig. 2. The form factors for the 0^+ (6.052-MeV) and 2^+ (6.916-MeV) levels are displayed in Fig. 3. The inelastic cross sections were obtained by comparison with the elastic-scattering cross section, whose absolute values were determined by phase-shift calculation. The calculation used the gen-

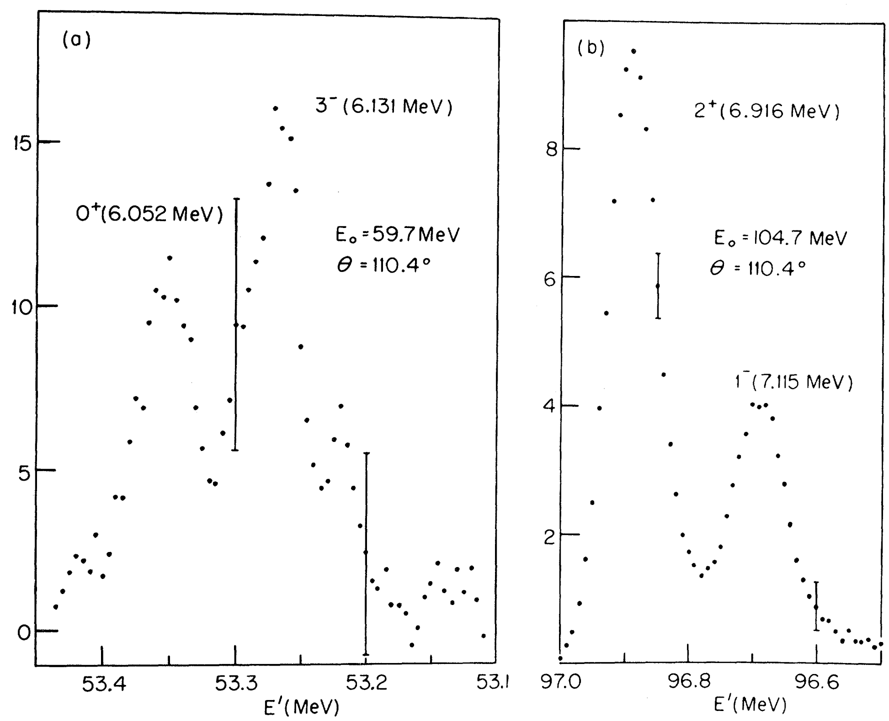

FIG 1. Inelastic electron-scattering spectra with backgrounds removed. (a) 0^+3^- doublet spectrum sorted into 5-keV bins. (b) 2^+1^- doublet spectrum sorted into 10-keV bins. One detector spans about 4 bins in each case. The vertical scales are in arbitrary units.

eralized harmonic-oscillator parameters $\alpha = 1.35$, $B = 1.81$ fm (corresponding to an rms radius of 2.67 fm) and gives a good fit to the available data[3] for $q \leq 1.9$ fm^{-1}. Transverse form factors have been extracted from the data and were found to be at most a few percent of the total form factors.

Errors in the form factors include the effects of counting statistics, uncertainties in the overall level of background subtraction, the influence of the radiation tail from the lower member of a doublet on its neighbor, and uncertainties in fitted line-shape parameters. The error bars shown in Figs. 2 and 3 represent reasonable estimates of the standard deviations based on the above effects and the influence of such instrumental effects as detector efficiencies, target-thickness uniformity, and current-monitoring accuracy.

The experimental form factor for the 3^- (6.131-MeV) state is compared with the random-phase-approximation calculation of Gillet and Melkanoff[4] in Fig. 2(a). These authors worked within the framework of 1p-1h (one-particle, one-hole) excitations, and used an oscillator length parameter of 1.75 fm. This form factor implies a radiative width of about 1.6×10^{-5} eV for the ground-state transition of the 3^- state, compared with the experimental value $(2.63\pm0.21)\times10^{-5}$ eV.[5] When normalized to yield the experimental width, the theoretical form factor fits the data very well.

In Fig. 2(b) comparison is made of the 1^- (7.115-MeV) form factor with a simple calculation based on a shell-model excitation from the $1p$ to the $2s$-$1d$ shell. The initial and final states were treated as pure $S=0$, $T=0$ configurations, and the spurious excitation of the center of mass was removed. Corrections were made for the proton size and center-of-mass effect. $F^2(q)$ has been multiplied by a factor of 3.6 to give a rough fit to the data. Comparison of this calculation with the experimental radiative width is not relevant since the transition at the photon point proceeds predominantly by $T=1$ impurities in the wave functions.

As shown in Fig 3(a), the 0^+ form factors of Boeker,[6] which are based on the 0p-0h, 2p-2h, and 4p-4h wave functions of Brown and Green,[7] are not consistent with the data.

One phenomenological interpretation of the even-parity states is the rotational model of Goldhammer and Prosser.[8] In this model the ground state of O^{16} is assumed to be dominated by two components, one spherical and the other deformed. The 0^+ (6.052-MeV) state is inter-

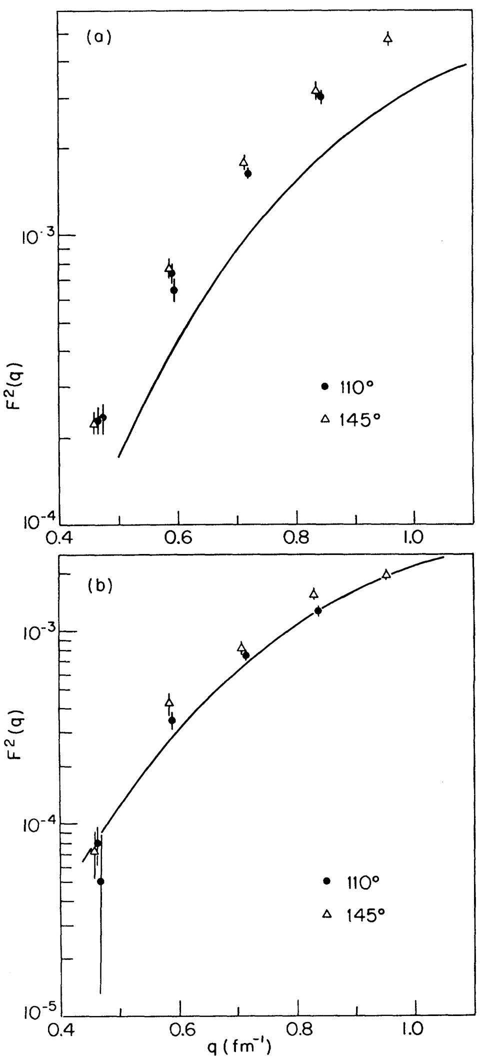

FIG. 2. (a) Form factor for the 3^- (6.131-MeV) state in O^{16}. The solid line is the form factor of Gillet and Melkanoff (Ref. 4). (b) Form factor for the 1^- (7.115-MeV) state. The solid line represents a simple shell-model form factor, multiplied by 3.6 (see text).

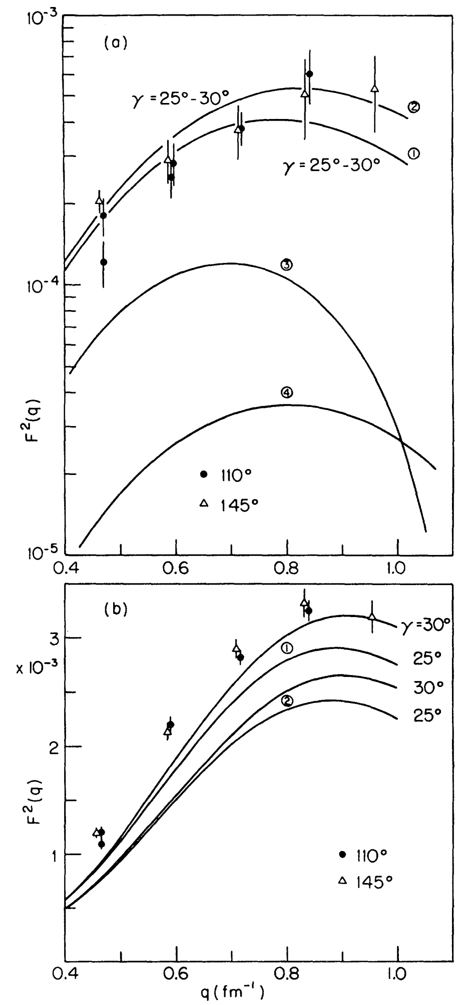

FIG. 3. (a) Form factor for the 0^+ (6.052-MeV) state. Curves 3 and 4 are the predictions of E. Boeker, Phys. Letters 24B, 616 (1967), using a deformed and spherical basis, respectively. Curves 1 and 2 are the predictions of the two-component model (see text) in which the 2^+ (6.916-MeV) ground-state radiative width was taken as 0.096 and 0.080 eV, respectively. (b) Form factor for the 2^+ (6.916-MeV) state. The solid curves are the predictions of the two-component model, as in (a).

preted as the orthogonal mixture of these components. The 2^+ (6.916-MeV) state is considered to be the first excited member of a rotational band based on the deformed component, and the 4^+ (10.353-MeV) and 6^+ (16.2-MeV) states are other members of the band. We extend this model and describe the deformed component with quadrupole deformation parameters β and γ. $\gamma = 0$ implies axial symmetry and the maximum asymmetry is represented by $\gamma = 30°$.[9] If we use the observed 2^+-4^+ energy separation as a scale factor, then the energy of the deformed component can be obtained as a function of γ from the known behavior of the rotational energy levels of a triaxially deformed nucleus.[10] The energy of the deformed component in turn uniquely prescribes the amplitudes of the components of two 0^+ states. The amplitude of the deformed component in the ground state is about 0.41 and 0.45 for $\gamma = 25°$ and $30°$, respectively. It is interesting to note that in this model, for $\gamma = 25°$, a 3^+ level and a second 2^+ level are predicted to lie within 3% of the 2^+ (9.847-MeV) and 3^+ (11.080-MeV) levels in O^{16}. The charge density of the deformed component is given by the harmonic-oscillator form

$$\rho(\vec{r}) = ce^{-(r/B')^2}[1+2(r/B')^2],$$
$$B' = B[1+\sum_\mu \alpha_{2\mu} Y_{2\mu}(\Omega)],$$

where $\alpha_{2\mu}$ is determined by β and γ.[11] We assume the spherical and deformed components of this model cannot be connected by a single-particle operator. The spherical state can be eliminated from further discussion by using the "known" elastic form factor to relate the spherical-state scattering amplitude to the deformed-state scattering amplitude.

The oscillator length parameter B and deformation parameter β are fixed by requiring the 0^+ (6.052-MeV) and 2^+ (6.916-MeV) form factors to yield, respectively, the monopole matrix element[12] (3.80 fm^2) and ground-state radiative width. Recent measurements of the radiative width of the 2^+ (6.916-MeV) ground-state transition give results between 0.080 and 0.100 eV.[13] For a width of 0.080 eV, we obtain $\beta = 0.57$ and $B = 1.76$ fm, while for a width of 0.96 eV we have $\beta = 0.63$ and $B = 1.73$ fm. The parameters β and B are relatively insensitive to the value of γ in the neighborhood of $\gamma = 25°$.

While it was possible to satisfy the model constraints with $\beta < 0$ (oblate ellipsoidal deformation) and $\gamma < 30°$, the required values of β and B ($|\beta| > 1$, $B < 1.55$ fm) were not considered to be reasonable.

Setting $\gamma = 30°$ yields a maximum ground-state radiative width for the second 2^+ state of this model of about 4×10^{-3} eV, compared with the experimental value for the 2^+ (9.847-MeV) level of about 6×10^{-3} eV.[14] It should be pointed out that this predicted width decreases very rapidly with decreasing γ. However, the observed branching ratio[15]

$$\frac{2^+\ (6.916\ \text{MeV}) \to 0^+\ (6.052\ \text{MeV})}{2^+\ (6.916\ \text{MeV}) \to 0^+\ (\text{gnd.})} = (2.5 \pm 0.4)\times 10^{-4}$$

requires $\gamma \leqslant 20°$. The form factors based on this phenomenological model are compared with the experimental form factors for the 0^+ (6.052-MeV) and 2^+ (6.916-MeV) states in Figs. 3(a) and 3(b), for $\gamma = 25°$ and $30°$. We note that large γ is preferred.

Although the comparison with the data is not exceptionally good, it is interesting that this simple two-component phenomenological model does come close to unifying many features of the low-lying even-parity states of O^{16}. We are in the process of extending this experimental work to the more highly excited states.

We wish to thank Dr. C. P. Browne for providing us with an accurate measurement of the energy separation of the 0^+ and 3^- states. We are grateful to Dr. G. Rawitscher for making available his phase-shift code for elastic scattering.

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