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RAPID COMMUNICATIONS

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Quadrupole and octupole radiation from ^{16}O near 39 MeV excitation

M. A. Kovash, B. Andersen-Pugh,* M. T. McEllistrem, J. K. Ternes, J. H. Trice, and J. L. Weil
Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506

S. L. Blatt,† H. J. Hausman, and D. G. Marchlenski
Department of Physics, Ohio State University, Columbus, Ohio 43210

A. D. Bacher
Indiana University Cyclotron Facility, Bloomington, Indiana 47405
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The angular distributions of cross section and analyzing power for the radiative capture reaction $^{15}\mathrm{N}(\vec{p},\gamma_0)^{16}\mathrm{O}$ have been measured at excitation energies of 35.0 and 39.0 MeV in ^{16}O. Gamma rays were detected in a large, self-shielded NaI spectrometer at eight angles from 23° to 155°. The complex reaction amplitudes associated with the capture channels leading to dipole, quadrupole, and octupole radiation have been extracted. The data at 39 MeV excitation indicate a quadrupole component $\sigma_{E2}/\sigma_{E1}=0.124\pm0.015$, and an octupole component $\sigma_{E3}/\sigma_{E1}=0.0051\pm0.0026$. The observation of high multipolarity radiation is discussed within the context of microscopic calculations which locate large components of the isovector quadrupole and octupole resonances within this region of excitation in ^{16}O.

Studies of the fundamental modes of excitation of the nuclear continuum provide information on the bulk properties of nuclear matter and on the influence of specific nuclear properties such as nuclear shape, or equivalently of the shell structure at high excitation. The individual multipole components of these excitations predominantly exhibit the particle-hole interactions within the mean nuclear field. The coupling of p-h configurations to additional degrees of freedom, such as surface modes of excitation, affects the detailed structure observed in each mode. Several calculations have been made of the distributions of high multipolarity strength in spherical nuclei using a variety of interactions and calculational techniques.[1–4] The results demonstrate that a clear test of these models requires experimental measurements of separated multipole strengths over a range of energies extending beyond 50 MeV in excitation.

Recent experimental results for elastic photon scattering have demonstrated the existence of substantial quadrupole strength in ^{16}O above the giant dipole resonance region.[5] These studies follow numerous previous photonuclear investigations of both isovector and isoscalar excitations of this nucleus.[6–10] The present investigation is intended to demonstrate that the distribution of quadrupole strength for radiative capture of polarized protons can be determined in a nearly model-independent manner in this energy region. Moreover, we find that these data, especially the measured analyzing powers at angles near 0° and 180°, display a strong sensitivity to the relatively small electric octupole amplitude.

In this Rapid Communication we present the initial results of measurements of cross sections and analyzing powers for the reaction $^{15}\mathrm{N}(\vec{p},\gamma_0)^{16}\mathrm{O}$ at excitation energies of 35.0 and 39.0 MeV. A more complete series of measurements is presently underway at energies from 28 to 48 MeV, and will be reported at a later time.

The present measurements were made at the Indiana University Cyclotron Facility, using extracted proton beams at 24.4 and 28.8 MeV. The magnitude of the beam polarization was typically 0.70, and was determined by measuring the asymmetry of elastically scattered protons from ^{4}He in a gas cell target. The beam was pulsed at a frequency of about 16 MHz, and individual beam bursts exhibited a time spread of less than $\frac{1}{3}$ nsec at the target location.

Gamma rays were detected in a NaI spectrometer[11] which included a NaI core element of diameter 20 cm and a length 25 cm, surrounded on the front and sides by an active NaI shield consisting of a 4 cm thick disk and a six-segment annulus also of 4 cm thickness. Both the core and the individual optically-isolated shield segments were instrumented with analog-to-digital converter and time-to-digital converter analyzers, operated in a CAMAC-based data acquisition system. Cosmic-ray backgrounds were detected in the active shield and rejected, while the measured energies from all eight NaI segments were digitally summed for events in which cosmic rays were not indicated. Figure 1 shows a typical pulse height spectrum of 39 MeV gamma rays where the transition to the ground state of ^{16}O is clearly resolved from transitions to the low-lying excited states, separated in energy by more than 6 MeV. The overall efficiency of the spectrometer was determined with the electron-photon shower code EGS4 (Ref. 12) to be 25% at 39 MeV gamma-ray energy, using a threshold of 36.3 MeV. We have confirmed the efficiency for our spectrometer at a gamma-ray energy of 10.8 MeV by comparing the results of an EGS4 calculation with the measured yield of the reaction ^{27}Al$(p,\gamma)^{28}$Si at the well-characterized resonance at $E_p = 992$ keV.[13] These results agree to within 5%. During the experiment the stability of the gain of the spectrometer at high total counting rates was maintained with an active feedback circuit coupled to the high voltage supply of the photomultiplier tubes.[14] Additionally, pulse pileup in the core NaI element was detected and rejected event by event to improve the reliability of the measured gamma-ray yields at the high counting rates observed.

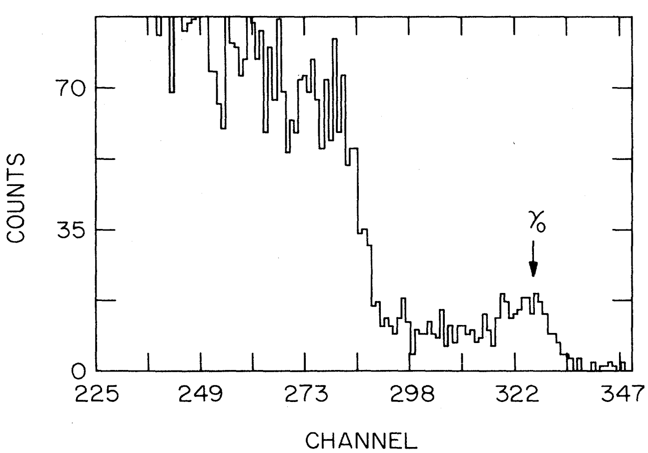

FIG. 1. Gamma-ray energy spectrum taken at 39 MeV excitation. The ground-state transition is indicated by the arrow; transitions to excited states in ^{16}O occur in channels 285 and below.

Data were collected from 23° to 155° in eight angular steps at a target-to-detector spacing of about 91 cm. Differences in time of flight (TOF) were used to distinguish gamma rays from the background of direct neutron groups produced in the target. The overall TOF resolution was 800 psec. Attenuation of slow neutrons was accomplished by placing boron around the lead shield of the detector.

The target consisted of a gas cell of 2.7 cm length pressurized to approximately 3 atm with ^{15}N gas enriched to 99%, and operated at room temperature. The gas cell contained beam entrance and exit windows of Havar with a total thickness of 12.5 μm. Beam passing through the target was deposited in a well-shielded iron beam dump approximately 5 m from the target location.

The cross-section angular distribution at 39 MeV excitation for the ground state gamma-ray transition is shown in Fig. 2(a). The data display the dominant dipole angular distribution, but a notable asymmetry about 90° also is evident, due to the interference between dipole and quadrupole components. In Fig. 2(b) the products of the measured differential cross sections and analyzing powers at this energy are displayed. The departure from the $\sin(2\theta)$ distribution indicative of pure dipole radiation is complementary evidence for an interference among multipoles.

In the reaction $^{15}\text{N}(\vec{p},\gamma_0)^{16}\text{O}$ the population of states with $J^\pi = 1^-$ proceeds through s- and d-wave capture with the complex amplitudes $^3S_1$ and $^3D_1$, as specified in LS coupling. Electric quadrupole radiation from $J^\pi = 2^+$ states occurs through the p- and f-wave capture amplitudes $^3P_2$ and $^3F_2$. Neglecting a contribution from g-wave capture, electric octupole radiation may proceed through the amplitude $^3D_3$. The amplitudes associated with each of these channels determine the angular distributions of cross sections and analyzing powers in a well-known manner.[15] We have used the observed distributions of $\sigma(\theta)$ and $\sigma(\theta) \times A_y(\theta)$ as input in a search algorithm which yields a solution for the amplitudes and relative phases associated with each channel. From these solutions the ratios of cross sections are given by

$$\frac{\sigma_{E2}}{\sigma_{E1}} = \frac{5}{3} \frac{|^3P_2|^2 + |^3F_2|^2}{|^3S_1|^2 + |^3D_1|^2}$$

and

$$\frac{\sigma_{E3}}{\sigma_{E1}} = \frac{7}{3} \frac{|^3D_3|^2}{|^3S_1|^2 + |^3D_1|^2} .$$

While more than one solution for the individual amplitudes can be found which are not distinguishable by the data, the above ratios of cross sections are much less sensitive to the variations among these solutions. At 39 MeV, for example, "solution A" yields amplitudes in the ratios:

$$\frac{|^3S_1|}{|^3D_1|} = 0.37, \quad \frac{|^3P_2|}{|^3F_2|} = 0.35 ,$$

whereas "solution B" yields the results:

$$\frac{|^3S_1|}{|^3D_1|} = 1.11, \quad \frac{|^3P_2|}{|^3F_2|} = 2.77 .$$

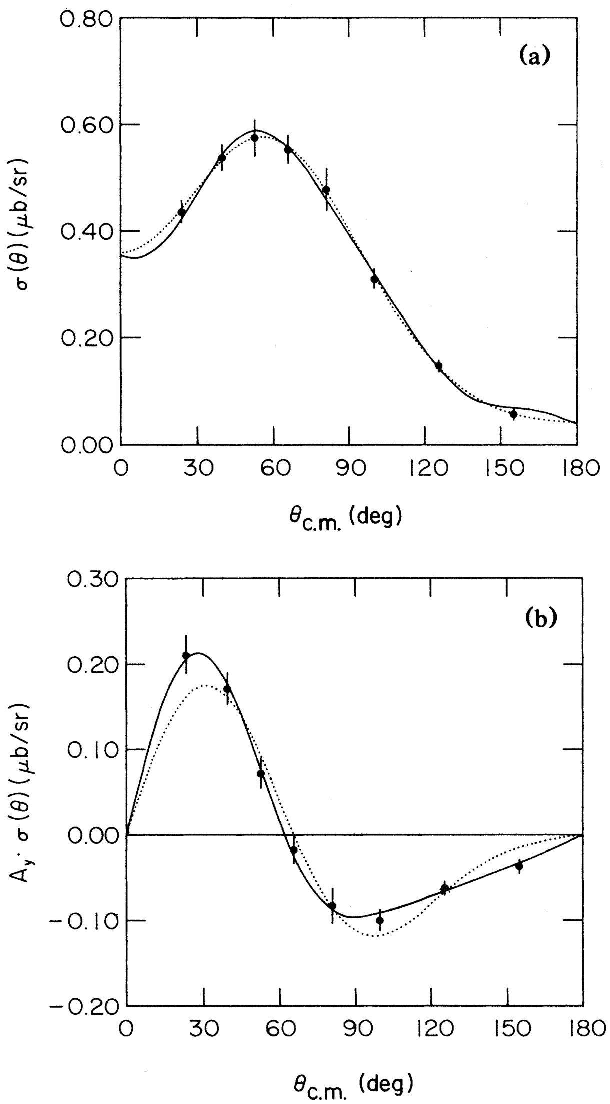

FIG. 2. (a) The measured differential cross sections are shown at 39 MeV excitation. The curves show the best chi-squared fits obtained when only $E1$ and $E2$ multipoles are retained (dotted curve), and when $E1$, $E2$, and $E3$ radiations are included (solid curve). (b) Measured angular distribution of cross section times analyzing power at 39 MeV excitation. The calculated distributions corresponding to the chi-squared fits to the amplitudes are shown.

A direct-semidirect model calculation[16] at this energy predicts the ratios:

$$\frac{|{}^3S_1|}{|{}^3D_1|}=0.28,\quad \frac{|{}^3P_2|}{|{}^3F_2|}=0.30\,,$$

which strongly favors solution A. The value of σ_{E2} corresponding to the accepted solution A is 22% smaller than that for solution B.

TABLE I. Measured ratios of cross sections for $E1$, $E2$, and $E3$ multipoles for excitation energies of 35.0 and 39.0 MeV.

E_x	35.0 MeV	39.0 MeV
σ_{E2}/σ_{E1}	0.056 ± 0.015	0.124 ± 0.015
σ_{E3}/σ_{E1}	0.0033 ± 0.0020	0.0051 ± 0.0026

The dashed curves in Figs. 2(a) and 2(b) show the results of the fit to the data at 39 MeV for which only $E1$ and $E2$ amplitudes are included in the search. While the cross-section data are adequately described, the product $\sigma(\theta)\times A_y(\theta)$ is poorly represented, especially at the data points at 23° and 155°. The value of χ^2 for this fit is 19.2. The solid lines in Figs. 2(a) and 2(b) show the results of including the amplitude ${}^3D_3$ in the search; the corresponding value of χ^2 drops to 1.8, thus providing strong evidence for the contribution of electric octupole radiation. At 35.0 MeV the value of χ^2 is likewise significantly lowered—by a factor of 3.3—with the inclusion of the $E3$ multipole.

In Table I the ratios of the measured quadrupole and octupole cross sections at both 35.0 and 39.0 MeV are shown; the relative fraction of quadrupole radiation is observed to double in this interval. A qualitatively similar increase in $E2$ strength is observed in the elastic photon scattering data[5] from ^{16}O, although these results indicate a much larger ratio, $\sigma_{E2}/\sigma_{E1}\approx\frac{1}{2}$, near 39 MeV.

The sensitivity of the capture data to the $E3$ amplitude results primarily from the availability of analyzing powers at 23° and 155°, even though the measured $E3$ total cross section is only a fraction of a percent of the total. That the $E3$ multipole could contribute in ^{16}O near 39 MeV was indicated by previous analyses of inelastic proton scattering data,[17] and by the model calculations.

We note that a similar level of agreement with the present data can be achieved by considering only $E1$, $E2$, and $M1$ multipoles in the amplitude search procedure. In order to fit the 39 MeV data, we find that the resulting magnetic dipole cross section is required to contribute 22% of the total. However, a calculation in the direct-semidirect model gives a ratio $\sigma_{M1}/\sigma_{\rm tot}=0.14\%$, i.e., a value too small to significantly affect the electric cross sections deduced from the data.

Further use of the radiative capture reaction with polarized protons in the energy range above the giant dipole resonance is clearly indicated as a means for identifying resonant multipoles. Such a program is now underway in ^{16}O, with additional capture measurements over the range $28\le E_x\le48$ MeV.

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*Present address: Luther College, Decorah, IA 52101.
†Present address: Clark University, Worcester, MA 01610.

[1]K. F. Lu and G. E. Brown, Nucl. Phys. **A265**, 385 (1976); K. F. Liu and Nguyen Van Giai, Phys. Lett. **65B**, 23 (1976).
[2]S. Krewald and J. Speth, Phys. Lett. **52B**, 295 (1974).
[3]G. F. Bertsch and S. F. Tsai, Phys. Rep. **18**, 125 (1975).
[4]M. Cavinato, M. Marangoni, P. L. Ottaviani, and A. M. Saruis, Nucl. Phys. **A373**, 445 (1982).
[5]W. R. Dodge *et al.*, Phys. Rev. C **28**, 8 (1983).
[6]S. S. Hanna *et al.*, Phys. Rev. Lett. **32**, 114 (1974).
[7]K. A. Snover, E. G. Adelberger, and D. R. Brown, Phys. Rev. Lett. **32**, 1061 (1974).
[8]P. C-K. Kuo, J. W. Jury, N. K. Sherman, and W. F. Davidson, Phys. Rev. C **30**, 1789 (1984).
[9]W. L. Wang and C. M. Shakin, Phys. Rev. Lett. **30**, 301 (1973).
[10]A. Hotta, K. Itoh, and T. Saito, Phys. Rev. Lett. **33**, 790 (1974).
[11]M. A. Kovash, in Proceeding of the LAMPF Workshop on Photon and Neutral Meson Physics at Intermediate Energies, Los Alamos, 1987, edited by H. W. Baer, H. Crannell, and R. J. Peterson, Los Alamos Report No. LA11177C, 417 (1987).
[12]Walter R. Nelson, Hideo Hirayama, and David W. O. Rogers, SLAC Report No. 265 (1985).
[13]J. Keinonen and A. Anttila, Commentat. Phys. Math. **46**, 61 (1976).
[14]M. A. Kovash and S. L. Blatt, Nucl. Instrum. Methods **163**, 113 (1979).
[15]R. G. Seyler and H. R. Weller, Phys. Rev. C **20**, 453 (1979).
[16]Hideo Kitarawa, code HIKARI, 1980 (unpublished).
[17]G. Perrin *et al.*, Phys. Lett. **68B**, 55 (1977).