PHOTONEUTRON CROSS-SECTION RESONANCES IN O^{16}†

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The cross section for the reaction $O^{16}(\gamma,n)O^{15}$ has been measured from threshold energy to 60 MeV using bremsstrahlung from the Iowa State University 70-MeV synchrotron. The O^{15} radioactivity yield curve was measured and the relative cross section extracted using least-structure analysis.[1-3] The resulting relative cross section, the result of least-structure analysis of the average of three yield curves, is shown in Fig. 1. The structure appearing above the giant resonance has appeared in essentially all of a very large number of analyses of individual and averaged yield curves. The errors in least-structure results are highly correlated and vary smoothly over the energy range; consequently error flags have been shown only at a few points. The horizontal error flags above the resonances do not represent imprecision in the resonance energy, but instead they represent the extent to which least-structure analysis would spread an infinitely narrow resonance in the cross section at that energy. This spreading is determined by the full width at half-maximum of a "resolution function" resulting from least-structure smoothing, and it is directly correlated with the average error of the yield function analyzed. Consequently, resolution of resonances above the giant resonance can be improved by improving data precision.

Three activation curves were measured in each of two separate experiments in which different samples, beam geometries, and energy control systems were used. In the first experiment data were taken and analyzed in 0.5-MeV increments, while in the second experiment data were taken and analyzed in 0.483-MeV increments.

Radioactivity was measured by detecting the annihilation radiation from the 123-second positron activity of O^{15} in a 3×3-in. NaI(Tl) scintillation crystal coupled to an EMI 9531B photomultiplier tube. Samples were bombarded for 3 min, one minute was allowed to elapse during which samples were removed from the synchrotron and placed in a standard counting geometry, and the radioactivity was counted for 3 min. Above 20 MeV, counting rates were typically 500 000 counts per minute. Stability of the counting system was held to $\pm0.25\%$ during the experiments by frequent checks with a Na^{22} standard source.

Samples were cylinders of boric acid 2.8 cm long compressed to a density of 1.4 g/cm^3. The

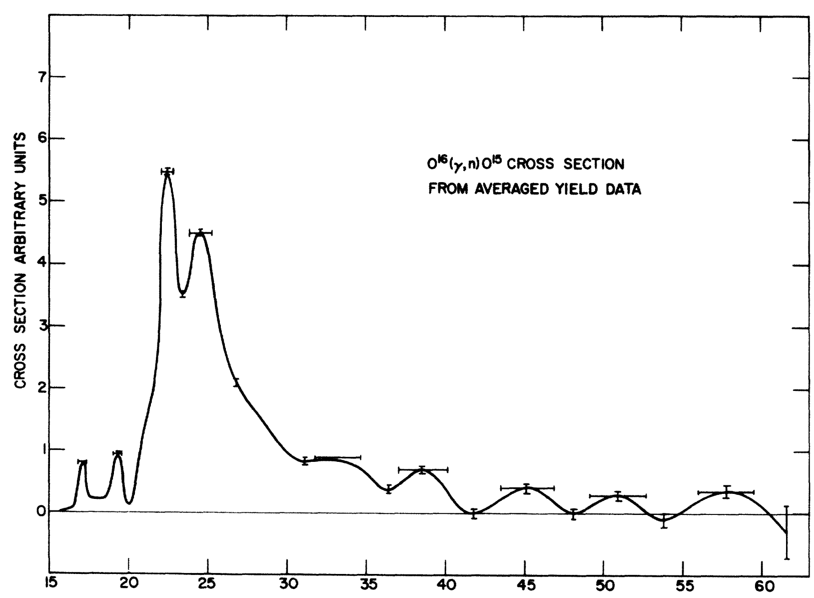

FIG. 1. Relative cross section for the reaction $O^{16}(\gamma,n)O^{15}$ calculated from the average of three radioactivity yield curves by the least-structure method.

samples were bombarded in eclipsing geometry following a collimator with photon attenuation factor of 5000. In the first experiment the collimator preceding the sample was cylindrical, while in the second experiment the collimator was conical with half-angle 0.02 rad and apex at the synchrotron internal target. The conical collimator was used to minimize the effect of scattering from the collimator walls on dosimetry.

Beam intensity was measured beyond the sample by a thick-walled aluminum ionization chamber sealed under positive pressure of dry nitrogen. Current output from the ionization chamber was delivered to an operational amplifier activity computer, the output of which was made proportional to sample activity as a function of time. The activity computer output voltage was recorded on an expanded scale Brown recorder making possible dosage readings of 0.1% reproducibility. The ionization chamber current was calibrated to the standard National Bureau of Standards (NBS) chamber response,[4] and the chamber response was corrected for radiation absorption in the sample at all energies.

For all data points above 20 MeV, counting statistics made a negligible contribution to standard deviation of the points. Systematic instabilities contributing to data fluctuations were found not to be energy dependent, and the average standard deviation of all points on the two averaged yield curves was close to 0.5%.

High-energy resonances such as those shown might be the result of a number of experimental imprecisions rather than a true property of the oxygen nucleus. Among these possibilities are (1) synchrotron beam movement, (2) nonlinearity of synchrotron energy control, (3) energy dependence of dosemeter, (4) extraneous activities and multiple processes, (5) bremsstrahlung spectrum effects, (6) method of data analysis, and (7) data statistics. Extreme care has been taken to investigate and rule out each of the listed sources of structure and a number of others.

(1) Before measurement of the activation curves, careful checks of synchrotron beam position were made by photographic methods and by bombarding arrays of tiny copper targets. No detectable beam shift was observed throughout the energy range of the experiment.

(2) Since nonlinearity of the energy control system could easily introduce structure into a cross section, the two experiments were performed using different energy control circuits operating over different ranges of the reference voltage power supply.

(3) In the NBS monograph describing the response of the standard ionization chamber,[4] some extreme limits are presented on the response curve which have a slightly different energy dependence than the average response. The averaged yield curve from the second experiment was used with each of these limit response functions to calculate a cross section in order to examine the effect of changes of ionization chamber response on high-energy structure. The resulting cross sections differed in a very minor way from the cross section calculated using the average response curve. One such result is presented in Fig. 2(f).

(4) At energies greater than 25 MeV, detectable amounts of longer lived activities, probably N^{13} and C^{11}, were observed in the samples after bombardment. The ratio of long-lived activity to O^{15} activity was measured as a function of energy, and the contribution of the long-lived activity to the yield curve was removed. The cross section for the reaction $O^{16}(\gamma, 2n)O^{14}$ has been reported to be very small compared to the (γ, n) cross section.[5] The effect of the 71-sec O^{14} activity on the yield curve was measured and found to be negligible.

(5) The data were analyzed using the Schiff integrated-over-angle bremsstrahlung equation.[6,7] Since the beam geometry was different in the two experiments, they were actually performed with slightly different bremsstrahlung spectra due to the angular dependence of the spectra. In order to investigate the effect of spectrum shape on the cross section, the average data from the second experiment were analyzed using two modified spectra. In one case the Schiff expression was used, but the spectra were calculated for energies 11 MeV higher than the experimental energies. The resulting relative cross sections were larger than normal due to the decrease in the number of photons at each point, but the cross-section shape and resonance positions remained essentially unchanged. In the second spectrum modification, the Schiff spectrum was modified to have an increased number of photons at the tip.[8] This modification resulted in a barely noticeable change in the cross-section shape. The results of the second spectrum modification are shown in Fig. 2(e).

(6) In order to preclude introduction into the data of any structure which might result in the appearance of high-energy cross-section resonances, all energy-dependent correction factors

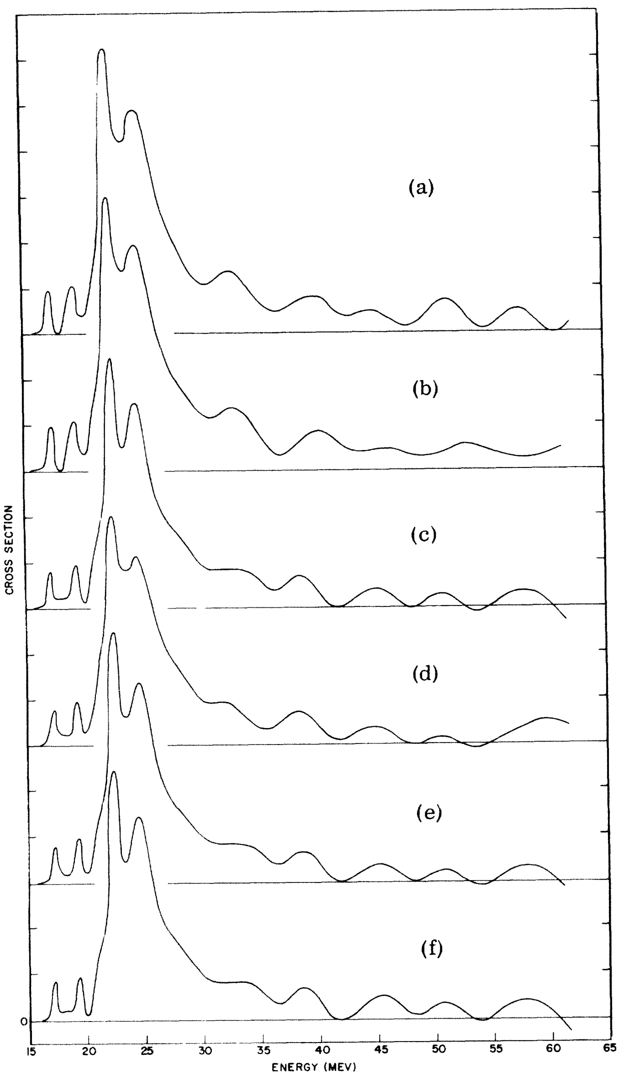

FIG. 2. Six cross sections from different yield curves or under different conditions by least-structure method: (a) from average of three yield curves of experiment I; (b) from an individual yield curve of experiment I; (c) from average of three yield curves of experiment II; (d) from an individual yield curve of experiment II; (e) from averaged yield curve of experiment II using modified bremsstrahlung spectra; (f) from averaged yield curve of experiment II using modified dosemeter response function.

were multiplied together to yield a single energy-dependent correction function. This correction function was smoothed by taking first differences, smoothing the first differences, and creating a new correction function using the smoothed first differences. The individual energy-dependent factors included the long-lived activity correction factor, the sample absorption factor, the NBS chamber response factor, and the energy under the bremsstrahlung curve at each energy. Only factors from the smoothed correction function were applied to the data.

(7) The possibility exists that the high-energy resonances observed are the result of statistical fluctuations in a given yield curve. The validity of the resonances is established by their consistent appearance in all of the analyzed yield curves. In Fig. 2 six examples are presented of the very many cross sections which have been calculated. The curves presented in Fig. 2 are (a), the result of averaging the yield curves of experiment I; (b), one of the individual results of experiment I; (c), the averaged result of experiment II; (d), an individual result of experiment II; (e), average result of experiment II using bremsstrahlung spectrum with modified tip; (f), average result of experiment II using one of the extreme limits of the NBS dosemeter response function.

The first four resonances in the cross section curve agree well with the results of many previous measurements through the giant resonance region,[9-14] as well as with theoretical predictions based on the particle-hole interaction in a shell model.[15-17]

Above the giant resonance five definite resonances are observed. The energies of these resonances are presented in Table I along with their areas. Since only relative cross sections are presented the areas under the high-energy resonances are presented as percentages of the cross section integrated to 30 MeV. The cross section integrated from 30 to 60 MeV appears to be about 38% of the cross section integrated from threshold to 30 MeV.

In calculations of $E2$ transition energies in O^{16} based on particle-hole interactions, Gillet and Vinh-Mau[18] have suggested that the two highest

Table I. Measured properties of resonances above the giant resonance.

Resonance energy[a] (MeV)	Percent of cross section integrated to 30 MeV
33.0 ±0.5	18.1%
39.7 ±0.5	7.9%
45.9 ±0.8	4.9%
51.6 ±0.8	2.4%
58.4 ±1.4	4.7%

[a]Errors on energies are standard deviations of six individual cross-section measurements. Systematic errors have not been taken into account.

2^+ $T=1$ states are almost pure $1s^{-1}1d_{3/2}$ and $1s^{-1}1d_{5/2}$ states with transition energies near 48.3 and 53.3 MeV. The energy separation of these levels reflects the $d_{3/2}$-$d_{5/2}$ splitting of about 5 MeV.

The resonances at 45.9 and 51.6 MeV are in reasonable agreement with these calculations as well as with levels observed by Isabelle and Bishop[19] at 44.8 and 49.3 MeV in an inelastic electron scattering experiment.

The remaining resonances may be associated with $E2$ transitions to $1f_{7/2}$ levels, with the recently discussed nuclear $E1$ overtones,[20] or the $3\hbar\omega$ resonances postulated by Danos.[21] Further insight into the nature of these resonances will probably have to await higher resolution experiments and angular distribution studies of the particular resonances.

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EXPERIMENTAL TEST OF THE CONSERVED VECTOR CURRENT THEORY ON THE BETA SPECTRA OF B^{12} AND N^{12}†

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The postulated universal V-A Fermi interaction[1-3] demands not only the identical form of interaction, but also the same strength for the bare coupling constants in the various weak decay processes. However, if renormalization of the vector coupling constant due to the pionic effects is required in nuclear beta decay, as it is certainly not in muon decay, then it is very hard to understand the near equality[4,5] of the observed vector coupling constants of these two decays. To explain the lack of renormalization of the vector coupling constants in beta decay, Feynman and Gell-Mann,[2] and earlier, Gershtein and Zel'dovich,[6] proposed a simple and elegant hypothesis, conservation of vector current (C.V.C.), which attributes the beta interaction strength not only to the bare nucleons, but also to the virtual pions, and intimately associates it with the symmetry property of strong interactions; that is, the charge independence of nuclear forces. To test the C.V.C. hypothesis Gell-Mann,[7] and Gell-Mann and Berman[8] suggested investigating the decays of the $T=1, J=1^+$ multiplet B^{12}, C^{12*}(15.11-MeV state), and N^{12} into the $T=0, J=0^+$ ground state in C^{12}. According to this conservation hypothesis, the interference term between the second-order vector interaction and the allowed term of the axial vector interaction should give a predictable shape correction factor and thus provide a sensitive test for the C.V.C. theory.[9]

Several laboratories[10,11] have, in the past, experimentally investigated the beta spectra of B^{12} and N^{12}. Although the ratio of the shape factors between these two spectra was found to be of the