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Brief Reports

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review**. *A Brief Report may be no longer than $3\frac{1}{2}$ printed pages and must be accompanied by an abstract.*

Bremsstrahlung from $^{16}O+p$ near the 2.66-MeV resonance

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The proton-oxygen bremsstrahlung cross sections have been measured at a bombarding energy of 2.74 MeV and at a scattering angle of 155°, for photon energies between 40 and 200 keV. The measured spectrum agrees well with the prediction of the Feshbach-Yennie approximation.

In a recent article,[1] we reported the proton-oxygen bremsstrahlung ($p\,^{16}O\gamma$) cross sections which were calculated near the 2.66-MeV elastic scattering resonance by using two soft-photon approximations, the Feshbach-Yennie approximation[2] (which belongs to a two-energy–one-angle approximation[3]) and a modified Low's approximation of Nutt *et al.*[4,5] (which belongs to a one-energy–one-angle approximation). In this paper, we wish to report our measurement of the $p\,^{16}O\gamma$ cross sections at an incident energy of 2.74 MeV, which is 80 keV above the resonance energy, for a scattering angle of 155°, and to compare our experimental results with the structure predicted by the Feshbach-Yennie approximation.

Our measurement provides a crucial test of the Feshbach-Yennie approximation. To understand why this experimental test is so important for the Feshbach-Yennie approximation, let us recall what we have learned from our study of the proton-carbon bremsstrahlung ($p\,^{12}C\gamma$) process near both the 1.7-MeV resonance and the 461-keV resonance. The $p\,^{12}C\gamma$ process near the 1.7-MeV resonance has been thoroughly studied by the Bologna group,[6] the Tokyo group,[7] and our Brooklyn group.[8,9] These groups have observed the resonance structure, in the form of a peak, in the measured $p\,^{12}C\gamma$ spectra, and the Brooklyn group has found that the observed peak can only be described by the full Feshbach-Yennie approximation, which includes both the principal (leading) term and the correction (second) term. In other words, the contribution from the correction term is significant in the vicinity of the resonance, and the calculation using only the principal term of the Feshbach-Yennie approximation cannot fit the observed peak. A puzzling contradiction, however, has also been found by the Brooklyn group in the same $p\,^{12}C\gamma$ process but near the 461-keV resonance.[10] In this case, the calculation using the principal term alone is in better agreement with experimental data than with the calculation using the full Feshbach-Yennie approximation. This discrepancy provides strong motivation for further testing of the Feshbach-Yennie approximation. The $p\,^{16}O\gamma$ process near the 2.66-MeV resonance is a particularly attractive case for testing the Feshbach-Yennie approximation because (i) the 2.66-MeV resonance is a well-isolated one, and (ii) the contribution from the correction term of the Feshbach-Yennie approximation is negligible.[1] In Ref. 1, we pointed out that the Feshbach-Yennie approximation predicts a bump structure in the $p\,^{16}O\gamma$ process at a forward angle (70°) in addition to the dip structure at 155°. It would have been interesting to observe the forward angle structure, although a measurement at that angle does not constitute a more stringent test of the Feshbach-Yennie theory. However, the forward angle measurement presented severe experimental difficulties owing to the fact that, under the conditions for this experiment, the elastic scattering peak from carbon in the target coincided exactly with the bremsstrahlung structure at 70°. Since the bremsstrahlung cross section is exceedingly small (about 10^{-8} of the proton-carbon elastic cross section), the random coincidences from even a small amount of carbon in the target rendered the forward angle data unreliable.

The experiment was carried out using the Brooklyn College 3.75-MeV Dynamitron accelerator. The experimental arrangement was basically the same as the one used for our earlier $p\,^{12}C\gamma$ measurements.[8,10] The target, consisting of NiO prepared from a 22-μg/cm^2 nickel foil by oxidization, was tilted 45° from the beam direction to prevent possible photon attenuation by the target frame. The beam current was typically 400 nA. Two silicon surface barrier detectors, each at 155°, were used to detect the scattered protons. Bremsstrahlung photons were detected by a 7.6×0.6 cm NaI crystal, sitting directly above the target outside the scattering chamber at a distance of 2.9 cm from the beam spot. A standard fast-slow coincidence circuit with a time resolution of about 8 ns full width at half maximum was utilized to identify bremsstrahlung events, which are characterized by coincidences between one of the proton detectors and the photon detector. Each event consisted of three signals: the energies of detected proton and photon, and the time interval between them. These events were digitized and saved in list mode for off-line analysis later. The final data have been corrected for photon detector efficiency and for attenuation by the detector housing. The efficiency correction was about 50% at 200 keV, and essentially zero below 100 keV. The attenuation correction ranged from 10% at 40 keV down to less than 3% above 100 keV.

The results of our measurements are shown in Fig. 1. In this figure, the ratio of the $p\,^{16}\mathrm{O}\gamma$ bremsstrahlung cross section to the elastic $p\,^{16}\mathrm{O}$ scattering cross section,

$$\sigma_{\mathrm{rel}} \equiv \frac{d^3\sigma}{d\Omega_p d\Omega_\gamma dK} \Big/ \frac{d\sigma_{\mathrm{el}}}{d\Omega_p} ,$$

is plotted as a function of the photon energy, K, at a bombarding energy 80 keV above the resonance and for a scattering angle of 155°. The error bars include both the counting statistics (typically about 15%) and uncertainties from the various corrections (typically less than 10%) combined in quadrature. These measured cross sections are compared with the theoretical predictions calculated from the Feshbach-Yennie approximation. The theoretical calculation includes corrections for the finite solid angles and energy resolutions of the detectors. Also shown for comparison are the results calculated from the modified Low's approximation of Nutt *et al.*

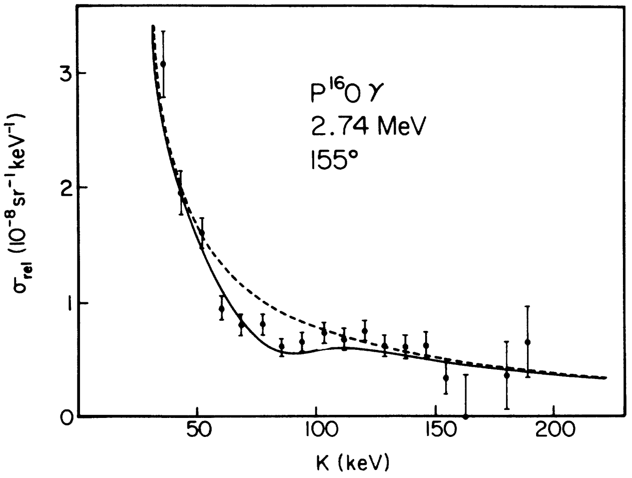

FIG. 1. The proton-oxygen bremsstrahlung cross sections relative to the elastic scattering cross section as a function of photon energy at an incident proton energy of 2.74 MeV and for a scattering angle of 155°. The solid curve represents the calculation using the Feshbach-Yennie approximation and the dotted curve represents the calculation using a modified Low's approximation of Nutt *et al.*

The measured spectrum, when compared with the spectrum calculated in the modified Low's approximation, shows a clear dip structure. This structure is well accounted for by the Feshbach-Yennie calculation. Good agreement between the Feshbach-Yennie calculation and experiment demonstrates that when the contribution from its correction term is negligible, the Feshbach-Yennie approximation can be used to describe bremsstrahlung emission in the region of a resonance.

The correction term of the Feshbach-Yennie approximation depends on the derivative of the elastic scattering T matrix with respect to the momentum transfer squared, t (or the scattering angle θ). The derivative term may cause problems if T changes very rapidly with t near certain scattering angles. In this case the soft-photon expansion converges slowly so that the contribution from the other high-order terms of the expansion may not be negligible. Therefore, the Feshbach-Yennie approximation, which involves only the first two terms of the expansion, may not be valid for describing some bremsstrahlung processes around some scattering angles when the contribution from the correction term is large. In these cases, it is possible to avoid the expansion of T in powers of t, by using a special two-energy–two-angle approximation developed recently by our theoretical group.[11] This new approximation, free of any derivative terms, can be used to describe both the $p\,^{12}\mathrm{C}\gamma$ data and the $\pi^{\pm}p\gamma$ data. For the $p\,^{16}\mathrm{O}\gamma$ process, the Feshbach-Yennie approximation and the two-energy–two-angle approximation are in very close agreement.

In conclusion, we have measured the $p\,^{16}\mathrm{O}\gamma$ cross section relative to the elastic cross section as a function of photon energy for an incident proton energy of 2.74 MeV, and a scattering angle of 155°. The measured spectrum shows a clear resonant structure which is well described by the Feshbach-Yennie approximation.

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