Bremsstrahlung from $^{12}C+p$ near the 1.7-MeV resonance

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The spectrum of bremsstrahlung radiation emitted by the scattering of protons by ^{12}C near the 1.7-MeV resonance has been studied at bombarding energies 76 and 146 keV above the resonance and 140 keV below the resonance. The spectra are in very good agreement with a complete calculation using the Feshbach-Yennie approximation which includes both the principal term and correction term.

[NUCLEAR REACTION Measurement of bremsstrahlung spectrum from $p+^{12}C$ near $E_p=1.7$ MeV.]

It was suggested by Eisberg, Yennie, and Wilkinson[1] that the observation of low energy bremsstrahlung radiation produced in the scattering by a nucleus of a nucleon or nucleus would be a good technique for measuring the time delay between the beginning and the end of a nuclear reaction, important information which would allow an unambiguous separation between compound nuclear reactions and direct interactions. Their classical treatment of the bremsstrahlung process was extended with a quantum mechanical treatment by Feshbach and Yennie,[2] whose method differs from the conventional treatment of the bremsstrahlung process first introduced by Low.[3] The Feshbach-Yennie approximation uses the scattering amplitudes evaluated at two different energies, the initial and final scattering energies, for calculating bremsstrahlung cross sections, whereas the soft-photon approximation of Low uses the elastic scattering amplitude evaluated at a fixed on-shell energy. The latter approximation gives the well-known $1/E_\gamma$ dependence for the photon spectrum whereas the former approximation would predict structure in the region of a resonance.

Since the cross section for proton-carbon bremsstrahlung is roughly 10^{-8} the elastic scattering cross section, no one has been able until recently to get good data on the process. In a series of three pioneering papers[4-6] a group from Bologna reported observing bremsstrahlung radiation in coincidence with protons scattered by ^{12}C near the 1734-keV resonance. Among the bremsstrahlung spectra measured by this group, the spectrum obtained at a bombarding energy of 1795 keV is the only one which has structure clearly exhibited at a photon energy corresponding to the difference between the incident proton energy E_p and the resonance energy E_R. The Bologna group, however, was unable to obtain quantitative agreement between the measured bremsstrahlung spectrum and the spectrum calculated from the principal term of the Feshbach-Yennie approximation if the parameters of the resonance obtained from elastic scattering data[7,8] were used. They were able to fit the 1795-keV experimental data only by introducing *ad hoc* a new set of resonance parameters.

This new set of parameters was studied by Jan *et al.*[9] They found that these parameters give poor agreement with the elastic scattering cross sections near the resonance for some scattering angles. Furthermore, they show that the bremsstrahlung spectrum obtained at 1795 keV is inconsistent with the elastic scattering data of Refs. 7 and 8, if the theory of Feshbach and Yennie is correct. Conversely, if the elastic scattering data and the bremsstrahlung data are consistent, then the bremsstrahlung data at 1795 keV cannot be described by the principal term of the Feshbach-Yennie approximation.

A further ambiguity in the theoretical interpretation of bremsstrahlung data arises from the pion-proton bremsstrahlung process reported by a UCLA group[10,11] at incident energies of 269 MeV and 298 MeV, just above the (3, 3) resonance at 195 MeV. In an analysis of this experiment, Liou and Nutt[12] show that the bremsstrahlung spectrum agrees well with the soft-photon approximation with little contribution from the resonance. Thus the validity of the Feshbach-Yennie approximation for describing bremsstrahlung emission near a resonance has not been established, warranting further experimental and theoretical studies.

We have extended the measurement of the bremsstrahlung cross section for $p+^{12}C$ near the 1734-keV resonance with the hope of confirming the findings of the resonance structure first reported by the Bologna group, of resolving the possible inconsistency between the elastic scattering data and the bremsstrahlung data obtained at 1795 keV by the Bologna group, and of clarifying the theoretical picture. Three bremsstrahlung spectra were measured at bombarding energies of 76 keV and 146 keV above the 1734-keV resonance and 140 keV below the resonance. In order to obtain spectra which possibly contain structure due to the resonance, we have expanded the measured range of the photon energy to 200 keV.

The experimental measurements involved the detection of scattered protons in coincidence with bremsstrahlung radiation. Protons from the Brooklyn College Dynamitron accelerator bombarded a 50-$\mu g/cm^2$ carbon target mounted on a lucite holder which was tilted 45° with respect to the beam. Protons scattered at a laboratory angle of 155° were stopped in a surface barrier detector subtending a solid angle of 4 msr. Bremsstrahlung photons were detected by a NaI crystal 76 mm in diameter and 6 mm thick, located 28 mm above and normal to the scattering plane. The beam, about 2 mm in diameter, was stopped in a Faraday cup 2 m from the target. The measured beam current was typically 400 na.

Figure 1 is a plot of the yield of elastically scattered protons at a laboratory angle of 155° as a function of incident bombarding energy E_p. The solid line drawn through the data points is for guiding the reader's eye and does not represent a fit to the data. This curve clearly shows a peak at $E_p \simeq 1734$ keV $\equiv E_R$, and a minimum just below the peak. The structure results from interference effects between two closely spaced levels of $\frac{5}{2}^+$ and $\frac{3}{2}^-$ in the compound nucleus ^{13}N.

Coincident events between bremsstrahlung photons and scattered protons were identified using standard fast-slow coincidence electronics with a time resolution of 12 ns full width at half maximum (FWHM). For each coincident event, photon and proton energies were recorded in a two dimensional pulse-height analyzer. In the analyzer display, real coincidences corresponding to bremsstrahlung events could be seen along a diagonal line in the E_γ, $E_{p'}$ plane, where $E_{p'}$ is the energy of the scattered proton. The diagonal line is defined by the kinematic restriction that the sum of the proton and photon energies $(E_{p'} + E_\gamma)$ must be constant and equal to the energy E_{el} of an elastically scattered proton, apart from a slight variation in the ^{12}C recoil energy. The number of elastically scattered protons was recorded independently for normalization.

Figure 2 shows the events in the E_γ, $E_{p'}$ plane at $E_p = E_R + 146$ keV. Each dot in Fig. 2 represents a coincident event. Because of the resolution of the detectors, the kinematic line becomes a kinematic band which is clearly visible in Fig. 2. Events below the kinematic band correspond to real coincident events in which photons did not deposit their full energies in the NaI crystal. The large number of events

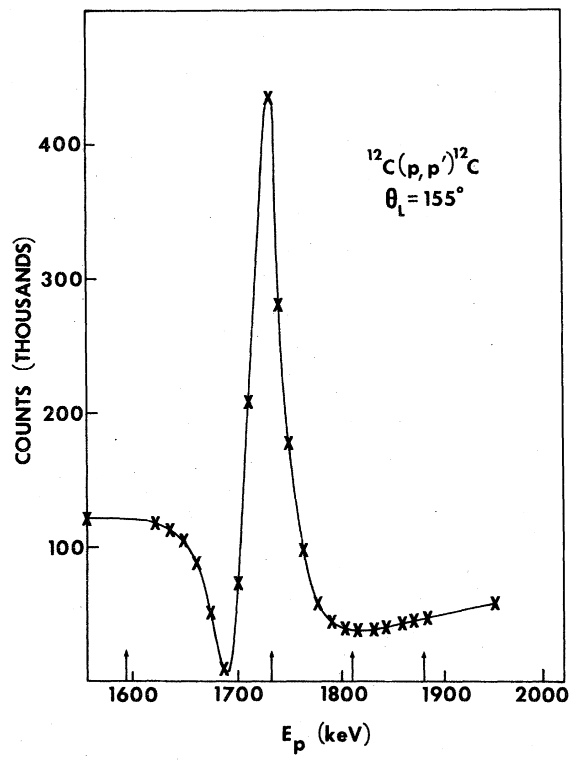

FIG. 1. Yield of elastically scattered protons from a 50-$\mu g/cm^2$ carbon foil at a laboratory angle of 155° as a function of the incident energy E_p. The arrows along the energy axis indicate the position of the 1734-keV resonance and energies 76 keV and 146 keV above the resonance, 140 keV below the resonance.

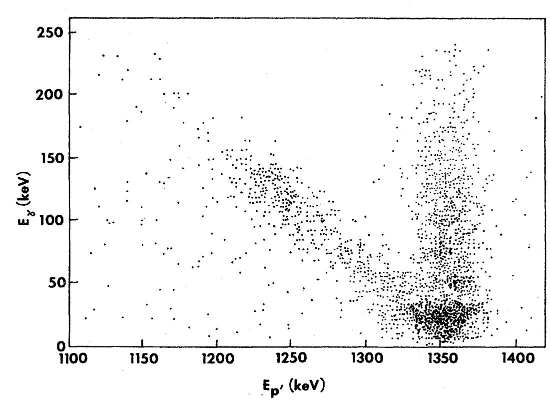

FIG. 2. Coincident events in the $E_\gamma - E_p'$ plane. Each dot corresponds to a coincident event. The incident energy was $E_R + 146$ keV.

at $E_{p'} = 1350$ keV $= E_{el}$ is due to accidental coincidences between photons and elastically scattered protons. Outside of this region, the number of accidental coincidences is negligible, as can be seen from the absence of counts above the kinematic band. An independent check of the accidental rate revealed its contribution to the final cross section to be less than 1%.

In analyzing the data, we projected onto the $E_{p'}$ axis, for $E_{p'}$ less then $E_{el} - 30$ keV, all events for which E_γ was in or below the kinematic band. We have thus included real coincident events in which the photons did not deposit their full energies in the NaI crystal. An independent check showed that these Compton-scattered events were consistent with the expected full-energy peak to Compton ratio. The projected spectra, as a function of $E_{p'}$, were replotted as a function of the corresponding photon energy E_γ, where $E_\gamma = E_{el} - E_{p'} - E$ (^{12}C recoil). These spectra were then corrected for NaI detector efficiency and detector housing attenuation. The corrections for detector efficiency varied from 40% at 250 keV down to 1% at 30 keV, while corrections for attenuation increased in the same interval from 3% to 20%. Near 100 keV the total correction was only about 5%. The resulting bremsstrahlung cross section, at each of the three bombarding energies, was divided by the corresponding elastic scattering cross section at 155°. The result

$$\sigma_{rel} = \frac{d^3\sigma}{d\Omega_\gamma\, d\Omega_{p'}\, dE_\gamma} \bigg/ \frac{d\sigma_{el}}{d\Omega_{p'}}$$

is plotted in Fig. 3 as a function of E_γ, corresponding to $E_{el} - E_{p'}$, for each of the bombarding energies. The error bars in Fig. 3 include both statistical errors and uncertainties in the systematic corrections for NaI detector efficiency and photon attenuation. Uncertainties due to counting statistics were typically about 30% while uncertainties in the systematic corrections were at most about 10%. These uncertainties were combined in quadrature to determine the final error bars.

The cross sections measured at the two bombarding energies above E_R clearly show structure, in the form of peaks, while the cross section measured below the resonance exhibits a simple $1/E_\gamma$ behavior. It is also clear that the position of the peak in photon energy approximately corresponds to the difference between the bombarding energy and the resonant energy, for both bombarding energies above E_R.

The solid curves in Fig. 3 represent the theoretical predictions of the Feshbach-Yennie approximation, averaged over the solid angle of the photon detector. Our calculations[13] include both the principal term and the correction term discussed by Feshbach and Yennie.

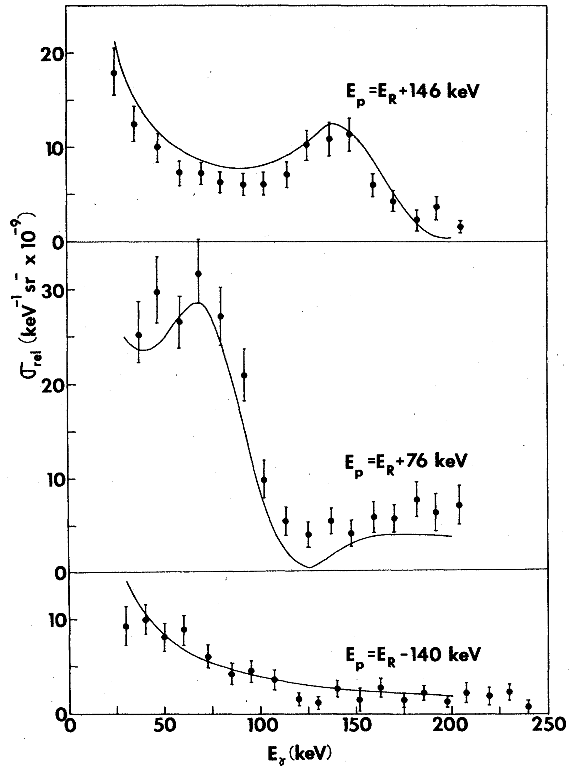

FIG. 3. The bremsstrahlung cross section relative to the elastic scattering cross section. The solid curve is the result of a complete calculation of the Feshbach-Yennie approximation with resonance parameters from elastic scattering data.

We calculated these terms in the form

$$\sigma_{rel} = \frac{\sigma_{-1}}{E_\gamma} + \sigma_0 ,$$

where the principal term σ_{-1}/E_γ depends upon the elastic scattering amplitude, and the correction term σ_0 depends upon the derivatives of the scattering amplitudes. We have found that the correction term, which is negligible at energies far from resonance, becomes significant in the region of a resonance. By including this term, we are able to achieve a satisfactory fit to the data, as shown in Fig. 3, using the elastic scattering resonance parameters from Ref. 8 without modification.

In conclusion, we have measured the proton-carbon bremsstrahlung cross sections near the 1.7-MeV resonance at three bombarding energies. The structure due to resonance effects which is clearly observed in two of our bremsstrahlung spectra can be successfully described by the Feshbach-Yennie approximation. Our work represents the first quantitative experimental confirmation of the Feshbach-Yennie approximation. We have achieved this confirmation by extending the range of previous measurements both in terms of bombarding energies and measured photon energies, and by including in our theoretical calculations a term which had been previously ignored in comparing theory with experiment. There is no inconsistency between our bremsstrahlung data and the elastic data.

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