

Calculation of p - ^{12}C elastic and p - ^{12}C bremsstrahlung cross sections near the 1.7-MeV resonances

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p - ^{12}C elastic and p - ^{12}C bremsstrahlung cross sections are calculated using various resonance parameters. We have found that among all the resonance parameters studied by us the Maryland parameters for p - ^{12}C is the only set which fits the elastic scattering data. We have also found that those resonance parameters which give good agreement with the bremsstrahlung data at 1795 keV tend to give poor agreement with the elastic data near the 1.7-MeV resonances. Our bremsstrahlung calculations are based on the Feshbach-Yennie approximation.

[NUCLEAR REACTIONS $^{12}\text{C}(p,p)^{12}\text{C}$ and $^{12}\text{C}(p,p\gamma)^{12}\text{C}$, $E_p=1.765$ – 1.895 MeV;]
calculate $d\sigma/d\Omega_p$ and $d^3\sigma/d\Omega_p d\Omega_\gamma dk$; deduced resonance parameters.

In a previous article,¹ we used two different approximations, the leading term of the soft-photon approximation (SPA) (Refs. 2, 3) and the principal term of the Feshbach-Yennie approximation (FYA),^{4,5} to predict the proton-carbon bremsstrahlung (p - $^{12}\text{C}\gamma$) cross sections in the region of the p - ^{12}C resonances. We found that at an energy very far from any resonant state these two approximations gave very similar results which were in very good agreement with the measurements of the Bologna group.⁶ We also found that the resonant structure observed in the experimental bremsstrahlung spectrum at a bombarding energy of 1795 keV could be described by the FYA if the parameters of the resonances, which were originally determined from the p - ^{12}C elastic scattering data by Armstrong *et al.*^{7,8} (this set of resonance parameters will be referred to as the Maryland parameters herein), were slightly varied. Let us make this point more precisely. When the Maryland parameters were used as an input for the FYA calculation, the predicted bremsstrahlung spectrum at the bombarding energy of 1795 keV was found in complete disagreement with the Bologna data. Since the bremsstrahlung cross sections are sensitive to the variation of the resonance parameters, the Bologna group have varied the parameters to fit their bremsstrahlung cross sections at 1795 keV. They have thus obtained a new set of parameters (this set of resonance parameters will be referred to as the Bologna

parameters herein) which is slightly different from the Maryland parameters. These two sets of parameters are listed in Table I.

We have studied the Bologna parameters by applying them to predict the elastic scattering cross sections. The results were then compared with the data of Armstrong *et al.* Surprisingly, these parameters give elastic cross sections which are in very poor agreement with the experimental data near the 1.7-MeV resonances for

TABLE I. Parameters of the resonances in $^{13}\text{N}^*$. γ^2 is the reduced width ($\text{MeV}/\text{cm} \times 10^{-13}$) and E_λ is the characteristic energy (keV).

J^π		$\frac{1}{2}^+$	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Set I (Ref. 7)	γ^2	7.58	0.515	3.550
	E_λ	951	3510	3609
Set II (Ref. 6)	γ^2	7.58	0.550	3.179
	E_λ	951	3541	3606
Set III	γ^2	7.58	0.420	3.100
	E_λ	951	3533	3604
Set IV	γ^2	7.58	0.450	3.00
	E_λ	951	3538	3605
Set V	γ^2	7.58	0.480	2.900
	E_λ	951	3543	3606

some scattering angles. This is primarily due to the fact that the elastic cross sections near the resonances for some scattering angles are also very sensitive to the variation of the resonance parameters. We have also applied the Bologna parameters to calculate the bremsstrahlung cross sections at 1765 and 1795 keV and have obtained a poor result in the soft-photon region $20 \text{ keV} \leq k \leq 40 \text{ keV}$. These findings indicate that the Bologna parameters are not the best-fit parameters one could obtain from the elastic and the bremsstrahlung data.

Now, the question is if we can find a set of new parameters which will give good fits to both the elastic and the bremsstrahlung data so that the existing discrepancy between the FYA calculation and the Bologna data at 1795 keV can be resolved. In an attempt to answer this question, we have recently made a careful search for new resonance parameters by fitting both the elastic data of Armstrong *et al.* and the bremsstrahlung data of the Bologna group. In this paper we wish to report some important results of our study, and to especially point out some difficulties involved in our search for new resonance parameters and to discuss their implications.

Our results can be summarized as follows:

(i) The calculated bremsstrahlung cross sections at the bombarding energies of 1765 and 1795 keV are very sensitive to the variation of the resonance parameters $E_\lambda(\frac{3}{2}^-)$, $E_\lambda(\frac{5}{2}^+)$, $\gamma^2(\frac{3}{2}^-)$, and $\gamma^2(\frac{5}{2}^+)$, especially the parameters $E_\lambda(\frac{3}{2}^-)$ and $E_\lambda(\frac{5}{2}^+)$, but these cross sections are not sensitive to the variation of the parameters $E_\lambda(\frac{1}{2}^+)$ and $\gamma^2(\frac{1}{2}^+)$. On the other hand, the calculated cross sections at the incident energy of 1895 keV are not sensitive to the variation of all these resonance parameters. (ii) The calculated elastic scattering cross sections near the 1.7-MeV resonances are also very sensitive to the variation of the resonance parameters $E_\lambda(\frac{3}{2}^-)$, $E_\lambda(\frac{5}{2}^+)$, $\gamma^2(\frac{3}{2}^-)$, and $\gamma^2(\frac{5}{2}^+)$, especially for $\theta_{c.m.} = 80^\circ - 100^\circ$. ($\theta_{c.m.}$ is the proton scattering angle in the c.m. system.) (iii) The Maryland parameters are the best-fit parameters obtained from the elastic data by Armstrong *et al.* Using this set of parameters as input for our FYA calculations, we have calculated three bremsstrahlung spectra at 1765, 1795, and 1895 keV. The predicted bremsstrahlung spectra at 1765 and 1895 keV are found to be in very good agreement with the Bologna data, but the spectrum at 1795 keV is in total disagreement with the data. These results have already been reported in Ref. 1. (See Fig. 1 of this reference.) Note that although the results obtained in Ref. 1 were based upon a simplified FYA calculation which included only

the leading term of the approximation, the discrepancy between the theory and experiment for the 1795-keV case would still exist even if the correction term of the FYA were included in the calculation. This fact was pointed out in Ref. 5. (See Figs. 2–4 of this reference.) In Refs. 5 and 9, it was also reported that the FYA calculations using the Maryland parameters at the bombarding energies of 1594, 1810, and 1880 keV were in very good agreement with the Brooklyn data.⁹ (iv) The Bologna parameters were obtained mainly by fitting the bremsstrahlung data at 1795 keV. However, as shown in Figs. 1(a) and 1(b), this set of parameters give very poor agreement with the elastic scattering cross sections near the 1.7-MeV resonances for $\theta_{c.m.} = 80^\circ$ and 90° . Moreover, as shown in Fig. 2 of Ref. 1, the calculated bremsstrahlung spectra using this set of parameters at 1765 and 1795 keV are also in poor agreement with the Bologna data in the soft-photon region $20 \text{ keV} \leq k \leq 40 \text{ keV}$. (v) Finally, by varying the resonance parameters $E_\lambda(\frac{3}{2}^-)$, $E_\lambda(\frac{5}{2}^+)$, $\gamma^2(\frac{3}{2}^-)$, and $\gamma^2(\frac{5}{2}^+)$ in order to fit the Maryland data and the Bologna data at 1795 keV, we have found a surprising result: The resonance parameters which give good agreement with the bremsstrahlung data at 1795 keV tend to give poor agreement with the elastic data near the 1.7-MeV resonances, especially for $\theta_{c.m.} = 80^\circ - 100^\circ$. In other words, it is very difficult to find a set of resonance parameters which will give good fits to both the elastic data of the

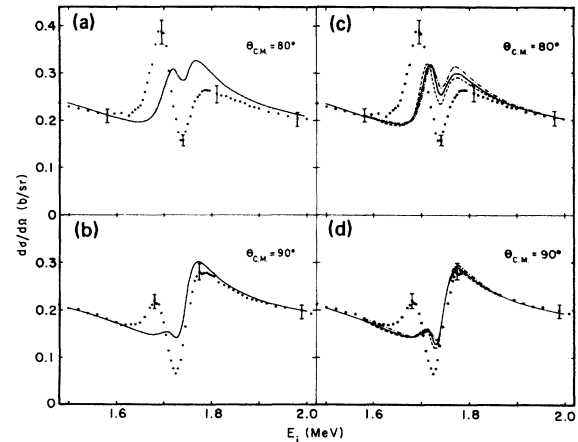


FIG. 1. p - ^{12}C elastic scattering cross section. The solid curves shown in (a) and (b) are the theoretical cross sections calculated using the Bologna parameters. (The set II parameters listed in Table I.) The dashed, dash-dotted, and solid curves shown in (c) and (d) are the theoretical cross sections calculated using the parameters of set III, set IV, and set V, respectively. (See Table I for these sets of parameters.) The dotted points are the experimental cross sections from Ref. 7.

Maryland group and the bremsstrahlung data at 1795 keV of the Bologna group. Some examples of this difficulty are illustrated in Figs. 1 and 2.

In Fig. 2, we have simultaneously varied the parameters $E_{\lambda}(\frac{3}{2}^-)$, $E_{\lambda}(\frac{5}{2}^+)$, $\gamma^2(\frac{3}{2}^-)$, and $\gamma^2(\frac{5}{2}^+)$ to fit the Bologna data at 1795 keV and have obtained three sets of new resonance parameters, which are listed in Table I (sets III, IV, and V). These three new sets of parameters give almost equally good fits to the Bologna data at 1795 keV. However, when these sets of parameters are used to calculate the elastic scattering cross section, they all give very poor agreement with the Maryland data near the resonances. This fact is shown in Figs. 1(c) and 1(d). Here, we should point out that the dashed curves in Figs. 2(a)–2(c) represent our calculation using the FYA which includes both the principal term and the correction term.

It is easy to understand that not only the bremsstrahlung cross sections but also the elastic scattering cross sections are sensitive to the variation of some resonance parameters near the 1.7-MeV resonances. This is because these cross sections are calculated from the same elastic scattering amplitude using the same resonance parameters. If the elastic scattering amplitude is sensitive to the variation of some resonance parameters, then we expect that both the elastic cross section and the bremsstrahlung cross section will be sensitive to the variation of the same parameters. Moreover, since the levels associated with the 1.7-MeV anomaly are $J^{\pi} = \frac{3}{2}^-$ and $\frac{5}{2}^+$, both the elastic cross section and the bremsstrahlung cross section may be sensitive only to the variation of the parameters $E_{\lambda}(\frac{3}{2}^-)$, $E_{\lambda}(\frac{5}{2}^+)$, $\gamma^2(\frac{3}{2}^-)$, and $\gamma^2(\frac{5}{2}^+)$, but not $E_{\lambda}(\frac{1}{2}^+)$ and $\gamma^2(\frac{1}{2}^+)$. An important result which we should emphasize here is that among all the resonance parameters studied by us the Maryland resonance parameters for p - ^{12}C is the only set which fits the elastic scattering data.

No definite conclusion can be drawn from our results (iii), (iv), and (v) because many different interpretations of these results are possible. We may interpret these results to imply that the particular set of the Bologna bremsstrahlung data at 1795 keV is inconsistent with the elastic data and/or that the FYA is inadequate to describe the bremsstrahlung spectrum at 1795 keV. Other

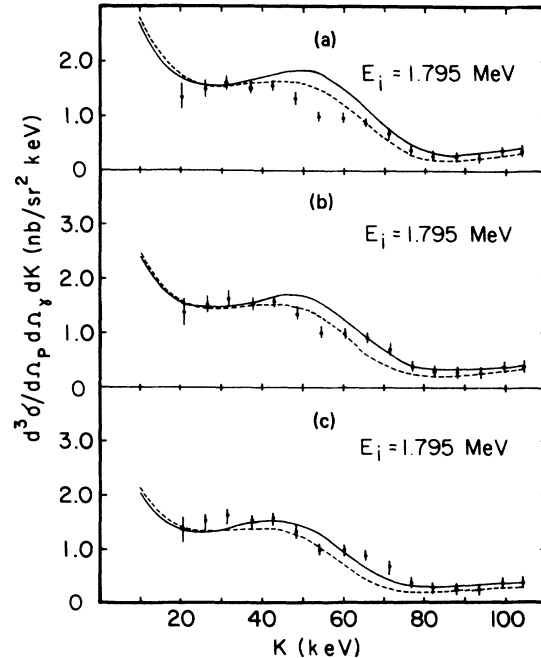


FIG. 2. p - ^{12}C bremsstrahlung cross section. Two curves shown in (a), (b), and (c) are the theoretical bremsstrahlung spectra calculated using the resonance parameters of set III, set IV, and set V, respectively. The solid curves represent the calculation using only the principal term of the FYA, and the dashed curves represent the calculation using both the principal term and the correction term of the FYA. The experimental data in all these figures are from Ref. 6.

interpretations may also be possible. Further study, both experimental and theoretical, is clearly required in order to resolve these ambiguities.

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