# Strong anomaly in the d-p bremsstrahlung

P. Bricault, R. J. Slobodrian, J. Pouliot, and R. Roy
*Laboratoire de Physique Nucléaire, Université Laval, Québec, Canada G1K 7P4*
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An anomaly in the d-p bremsstrahlung cross section, observed previously near the breakup threshold, was unexplained on the basis of an on-shell calculation of the cross section. An improved experiment using a solid target of $(CH_2)_n$ has confirmed the energy of this strong anomaly. Off-shell and various neglected on-shell effects are prime candidates for its explanation. Estimates of these effects are calculated. Means of implementing necessary experimental improvements of the art are discussed.

Reasons for studying bremsstrahlung processes in nuclear interactions[1–3] are now well known. They constitute the simplest reaction beyond pure elastic scattering because the final state consists of two strongly interacting fragments plus a photon. They are essential for a proper understanding of the nuclear interaction and its many applications in diverse areas of nuclear physics. The parameters of the nuclear potentials have been obtained predominantly from elastic scattering experiments, and thus on-shell observables of the interaction are used to construct potential models. However, nuclear processes other than elastic scattering depend on off-shell properties. Elastic scattering experiments cannot provide information about the off-shell properties of the nuclear interaction. The bremsstrahlung in nuclear interaction is the simplest and the most direct process that can be used for that purpose because there are only two strongly interacting particles. Other inelastic processes, such as particle production, involve three or more strongly interacting particles, which greatly complicate the theoretical analysis. However, bremsstrahlung cross sections are small, one event per $10^6$—$10^7$ elastic particles, which makes measurements difficult and the time required for data accumulation becomes very long. Furthermore, good theoretical calculations needed for comparison to experiment are exceedingly difficult to carry through.

The proton-deuteron system is particularly interesting because it involves a nucleon and a bound state of two nucleons, allowing a complexity beyond the simple nucleon-nucleon interaction, involving threshold effects at low energies. Previous measurements were done between 6.3 and 7.1 MeV using a Harvard geometry at 20°-20° in the laboratory system. An anomaly in the cross section near the breakup threshold of the deuteron was observed.[4] An approximate theoretical cross section, from the expression of Signell[5] [Eq. (1)] based on the first term of the Feshbach-Yennie on-shell expansion[6] can be expressed as

$$\frac{d^2\sigma}{d\Omega_p d\Omega_d}=\frac{1}{(2J_d+1)(2J_p+1)}A\frac{P_d e^2}{m_d\pi}\left[Z_d-\frac{m_d}{m_p}Z_p\right]^2 \times\mathrm{Tr}\{B\,|\,t_i\,|^2+|\,t_f-Ct_i\,|^2\}\ , \tag{1}$$

with

$$A=\sin^2\theta_d\sin^2\theta_p\{\sin(\theta_d+\theta_p)\times[\sin^2(\theta_d+\theta_p)-\sin^2\theta_p-(m_d/m_p)\sin^2\theta_d]^2\}^{-1}\ , \tag{2}$$

$$B=\left[\frac{m_d+m_p}{m_p}\right]^2\frac{\sin^2\theta_d\sin^2\theta_p}{\sin^2(\theta_d+\theta_p)}\ , \tag{3}$$

and

$$C=\frac{m_d+m_p}{m_d}\frac{\sin\theta_p\cos\theta_d}{\sin(\theta_d+\theta_p)}-\frac{m_d}{m_p}\ . \tag{4}$$

$P$ indicates momentum, $m$ the masses, and $\theta$ the laboratory angles; $t_i$ and $t_f$ are the elastic amplitudes. We have set $h=c=1$. A calculation based on expression (1) and existing phase shifts known at widely spaced energies produced a monotonic dependence of the cross section with deuteron energy. In addition, the absolute value predicted was too high. Failure to account for the energy dependence in terms of Eq. (1) could be attributed to a variety of reasons. In particular, the elastic scattering phase shifts used for the calculation of the elastic amplitudes were known at widely spaced energies, 0.7 MeV steps in the c.m. system,[4] whereas the bremsstrahlung results had been obtained at 0.3 and 0.5 MeV steps; hence interpolations were required in the calculations. New experiments were done for the determination of the elastic scattering phase shifts. The results obtained by Lahlou *et al.*[7] showed variations of the $^2S_{1/2}$ and $^4P_{1/2}$ phase shifts describing the elastic scattering near the breakup threshold. The calculations of the d-p bremsstrahlung cross section using Eq. (1) were repeated using the new phase shifts,[8] and they showed a small anomaly near the breakup threshold (Fig. 1). The agreement with experiment was fair, and due to the large error bars it was difficult to claim that other effects could be present. Thus, new measurements were performed. To reduce the time needed for data accumulation, a solid target of polyethylene, $(CH_2)_n$, was used. The thickness of the target was 0.94 mg/cm$^2$ and we made the measurements between 6.38 and 7.08 MeV at the same angles as in the earlier experiment. These new results show again a clear disagreement with the theoretical curve, particularly near and at the breakup

 

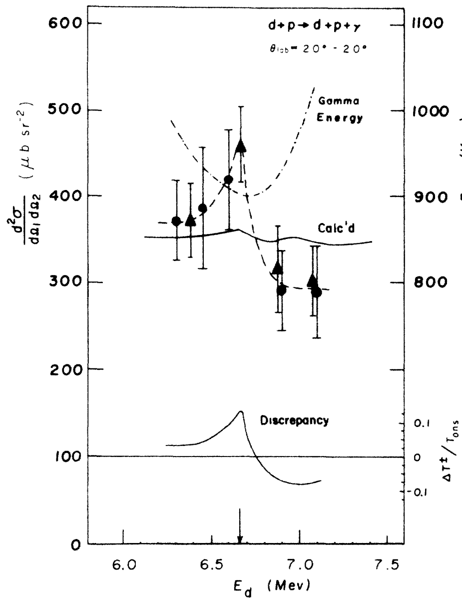


FIG. 1. Bremsstrahlung cross sections in the d-p interaction as a function of the deuteron energy. The dots are the previous results obtained from Ref. 4, and triangles are the new results. The curve labeled Calc'd is obtained from Eq. (1). The dashed-dot line is obtained from an energy average of the gamma rays produced in the interaction as a function of the deuteron energy. At the bottom of the figure we have plotted $|\Delta T^{\pm}|/T_{\rm ons}$ as a function of the deuteron energy.

threshold, 6.67 MeV in the laboratory system. The new points are represented by triangles in Fig. 1. The strong singularity in the off-shell d-p amplitudes[9] is a candidate for the explanation. Moreover, this type of experiment can provide a quantitative basis for a determination of such off-shell amplitudes and determine a suitable potential model, as is well known.

It is relevant to note that in the present case $E_\gamma/2E_{\rm c.m.}$ is not much smaller than unity, and thus the approximation in the general expression of Ref. 6,

$$\boldsymbol{\epsilon}\cdot\mathbf{M}_{fi} \cong \frac{N}{A\omega}[\boldsymbol{\epsilon}\cdot\boldsymbol{\beta}_f T(E_i) - \boldsymbol{\epsilon}\cdot\boldsymbol{\beta}_i T(E_f)] ,$$

leading to Eq. (22) of the same reference, is probably not warranted. These expressions lead to the closed form expression (1) shown above for the correlation cross sections. We have calculated the average values of $E_\gamma$ over the kinematic locus in the new expeirmental results (Fig. 1). They indicate a strong variation of the average of $E_\gamma$ over the locus determined by our finite geometry.

From considering simply the partial wave representation of scattering in the presence of inelastic thresholds, anomalies appear in the real part of phases related to the imaginary part as expressed by

$$\mathrm{Re}(\delta_l(k)) = \frac{2k}{\pi}\int_{-\infty}^{\infty}\frac{\mathrm{Im}(\delta_l(k'))}{k^2-k'^2}dk' .$$

Correspondingly, a potential model for the system should entail a change of a real $V$ into the complex potential $U+iW$. There is a sudden discontinuity in a Hamiltonian representation of the system, with a singularity as a function of energy and momentum through the breakup threshold. This will affect both the on-shell scattering amplitudes and the off-shell amplitudes as well. The study of the elastic channel has provided evidence of a rapid variation of the on-shell scattering amplitudes. These have, in turn, given rise to an oscillation of the calculated bremsstrahlung cross section, but not quite sufficient to account for the observed (and now confirmed) variation of the bremsstrahlung cross section through the breakup threshold. It is thus reasonable to estimate the discrepancy by writing

$$T^{\pm} = T_{\rm ons} + \Delta T^{\pm} ,$$

where $T_{\rm ons}$ is the "on-shell" transition matrix element,

$$T_{\rm ons} = T(\boldsymbol{\beta}_f \,|\, \boldsymbol{\beta}_i)$$

in the notation of Ref. 6. This will entail the appearance of the terms $|T_{\rm ons}+\Delta T^{\pm}|^2$ in the cross section expressions. The leading terms are those affected by $T_{\rm ons}$. From the difference between the theoretical curve and the experimental points we have obtained $|\Delta T^{\pm}|/T_{\rm ons}$,[10] shown in Fig. 1 as a function of the deuteron energy. This estimate is rather crude, but points out the relevance of improving the experimental conditions and the theoretical approach to extract information on the nucleon-deuteron interaction and the three nucleon system. The development of new techniques is necessary, as the present state of the art implies very long periods of data accumulation. One possible way to achieve needed improvements would be to combine a magnetic analysis with solid state detector techniques in order to eliminate the elastic scattering flux limiting the beam intensities used in bremsstrahlung experiments.

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[10]Only the magnitude of the discrepancy has been calculated.