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23 JAN. 1979

TRI-PP-78-28
Dec 1978

1021-PP 78-28
C1
- 2 -

"Forbidden" asymmetries and choices of geometry in
proton-proton bremsstrahlung

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Abstract

It is shown that the "forbidden" asymmetries in proton-proton bremsstrahlung, suggested by Moravcsik as a source of off-shell information, are suppressed by just one power of the photon momentum k , and still contain large contributions from purely on-shell effects. Two separate criteria—large off-shell parameter Δm^2 and large soft-photon parameter k/E_0 —are emphasized as necessary for a "good" geometry, and some examples of such geometries are given.

(submitted for publication)

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In principle proton-proton bremsstrahlung (ppv) provides information on off-shell aspects of the nucleon-nucleon force, though so far little such information has been obtained, both because experiments are very difficult and never seem to be quite far enough off shell and because there has not been enough theoretical input prior to the experiments indicating where to look and what to look for. Thus the recent experiments,¹⁻³ with the exception of the highest energy photons in the UCLA² experiment, are described fairly well by purely on-shell soft-photon calculations.⁴

Lately there has been renewed interest in ppv, as emphasized, for example, at a recent workshop⁵ on ppv, and several new experiments are under consideration,⁶ so it is particularly appropriate at this time to look for aspects of ppv, e.g. polarization phenomena,^{7,8} which might be more sensitive to off-shell effects.

A most exciting development in this area has been the recent suggestion of Moravcsik¹⁰ that one should look at certain "forbidden" asymmetries which vanish in the on-shell limit because of some general selection rule, but which can be non-zero for ppv, and hence are presumably particularly sensitive to off-shell information.

The purpose of this article is to analyse this very interesting suggestion in detail and understand its connection with the generalized Burnett-Kroll theorem¹¹ which states that *any* spin correlation in a radiative process is given through the first two orders in the photon momentum k purely by on-shell information.

The results of such analysis indicate that "forbidden" asymmetries do contain in addition to off-shell information a substantial on-shell contribution which is, however, suppressed by one power of k relative to

the cross section or the usual transverse asymmetry. Thus some increase in sensitivity is achieved, though not as much as originally hoped.

For both polarization and cross-section measurements one must choose kinematic conditions which maximize the possibility of off-shell information. In the last part of the paper criteria for this choice are discussed and particular experiments suggested which may hold promise of interesting off-shell information.

First consider the elastic process defined by the four-momenta $p_1 + p_2 = p_3 + p_4$ and the $pp\gamma$ process defined by $p_1' + p_2' = p_3' + p_4' + k$, where $p_i' = p_i + 0(k)$. The specific choice of mapping $p_i' \rightarrow p_i$, and hence of co-ordinate system, affects results only in the third term in an expansion in k .^{11,12} Thus take $\hat{p}_1 = \hat{p}_1' = \hat{z}$ and let $\vec{p}_3$ and $\vec{p}_3'$ be in the x - z plane. Define the asymmetry $A_i \equiv (d\sigma_+ - d\sigma_-)/(d\sigma_+ + d\sigma_-)$, where $d\sigma_{\pm}$ are the differential cross sections with incident beam polarized along $\pm \hat{i}$. With the above choice $A_y \equiv A_{\perp}$ is transverse to the x - z plane, and A_x, A_z , taken collectively as $A_{||}$, are in the plane. Let s_1 be the spin four-vector of the incident proton.

For elastic scattering the only possible spin observables are of the form $\epsilon(s_1, p_1, p_2, p_3) \equiv \epsilon_{\alpha\beta\gamma\delta} s_1^\alpha p_1^\beta p_2^\gamma p_3^\delta$ and $s_1 \cdot p_1$. Only the former conserves parity and it vanishes also unless $\hat{s}_1$ is transverse to the scattering plane. Hence for elastic scattering $A_{\perp} \neq 0$, $A_{||} \equiv 0$ as is well known. For $pp\gamma$, however, the additional vector available allows the forms $\epsilon(s_1, p_1', p_2', p_3')$, $\epsilon(s_1, k, p_2', p_3')$, $\epsilon(s_1, p_1', k, p_2')$, and $\epsilon(s_1, p_1', p_2', k)$ and the parity-violating terms $s_1 \cdot p_i'$ and $s_1 \cdot k$. For the coplanar case the ϵ 's all reduce to $\epsilon(s_1, p_1', p_2', p_3')$ and as before $A_{\perp} \neq 0$, $A_{||} \equiv 0$, but for the non-coplanar case $\hat{s}_1$ is not required to be transverse and in general both $A_{\perp}$ and $A_{||}$ are non-zero. $A_{||}$ is in this case a "forbidden"

asymmetry, since it vanishes by parity arguments in the elastic limit.

In the soft-photon approximation (SPA)^{13,15} $A_{\perp}$ and $A_{||}$ can be easily calculated, e.g. via Eq. (2.4) of Ref. 15, and depend only on on-shell information. An example of such results is shown in Fig. 1. One sees immediately that $A_{||} \equiv A_x, A_z \rightarrow 0$ as $k \rightarrow 0$ and $A_{\perp}$ reduces to the $A_{\perp}$ for elastic scattering. For $k \neq 0$, however, there are sizeable on-shell contributions to $A_{||}$, so that the original suggestion¹⁰ of simple proportionality to off-shell information does not hold.

To understand this in more detail consider the generalization of the Burnett-Kroll theorem¹¹ which indicates that any spin correlation can be calculated through two orders in k from on-shell information. Specifically, in the notation of Ref. 11

$$|M_{pp\gamma}|^2 = \left[\hat{Q}^2 + \hat{Q} \sum_i \left(\hat{Q}_i D_i \cdot \frac{\partial}{\partial p_i'} + (Q_i + \kappa_i) E_i \cdot \frac{\partial}{\partial s_i} \right) + \frac{\kappa_i}{m^2} s_i \cdot D_i p_i' \cdot \frac{\partial}{\partial s_i} \right] |M_{pp}|^2 + O(k^0),$$

where $\hat{Q}$, D_i , E_i are (respectively) $O(1/k)$, $O(k^0)$ and $O(k^0)$ functions of the p_i' . $|M_{pp}|^2$ is the square of the elastic amplitude and can be taken, for example,¹⁶ as $|M_{pp}|^2 = M_1 + M_2 \epsilon(s_1, p_1', p_2', p_3')$.

Since $p_i' = p_i + 0(k)$, the leading contribution to A_i , coming from the $\hat{Q}^2 M_2$ term with $p_i' \rightarrow p_i$, is $\sim \epsilon(s_1, p_1, p_2, p_3)/k^2$ and thus contributes only to $A_{\perp}$. Other pieces of the $\hat{Q}^2$ term coming from the $O(k)$ terms in the mapping $p_i' \rightarrow p_i$ are of the form $\epsilon(s_1, p_i, p_j, k)/k^2$ and will contribute to $A_{||}$, but only in $O(1/k)$. Similarly, using explicit expressions¹¹ for D_i and E_i one sees that the contributions to $A_{\perp}$ and $A_{||}$ from the $\hat{Q} M^2$ terms are now both of $O(1/k)$. Thus $A_{||}$ is suppressed, but by only one power of k . The $O(1/k)$ on-shell terms are still present and it is their contributions [together with some on-shell $O(k^0)$ contributions which are

included in the numerical work but not in the B-K formula above] which are seen in Fig. 1 for $k \neq 0$.

Thus since one usually wants to suppress *all* soft-photon terms, the suppression of A_1 by only one power of k will not be decisive. However, the asymmetries involve different combinations of amplitudes than the cross section, and it has already been shown that model calculations for A_1 both differ strongly from SPA results⁷ and are sensitive to changes in off-shell behaviour of the nucleon-nucleon potential.⁸ Presumably a similar situation holds for A_{11} , so a measurement of A_1 still remains very interesting. Clearly, however, there is a need for explicit model calculations of A_1 for a variety of geometries.

For A_1 and A_{11} and also the cross section, it is crucial to choose the geometry of an experiment so as to maximize the amount of useful information. There are two major conditions which must be met. First the geometry must allow for sufficiently off-shell amplitudes, and second the photon energy must be sufficiently high to get out of the soft-photon region. That these two conditions are *distinct* and favoured by *different* geometries has not been fully appreciated in the past.

To characterize off-shell aspects, an appropriate parameter is simply the square of the four-momentum of the off-shell nucleon leg. More precisely, averaging over the four possibilities, define $\Delta m^2 = \frac{1}{4} \sum_i [(p_1' + k)^2 - m^2] / 4m^2 = (k \cdot p_1' + k \cdot p_2' + k \cdot p_3' + k \cdot p_4') / 2m^2$. Thus Δm^2 measures directly the average amount by which the nucleon four-momenta squared differ from the on-shell value m^2 . For a fixed geometry Δm^2 increases with increasing incident energy; thus if this were the only criterion one would try for the highest energies possible.

A second restriction, however, is given by the Low¹⁴ theorem which

shows that the leading two terms in an expansion of the amplitude in powers of k/E_0 are given purely by on-shell information. Thus large Δm^2 is not enough; one must also have k/E_0 sufficiently large that third and higher-order terms are significant.

The quantity E_0 is a somewhat ill-defined energy parameter which sets the scale of the expansion. The average nucleon kinetic energy is a conventional choice¹⁷ although other choices have been proposed.^{14,18} In a *quantitative* sense attempts to define E_0 precisely are probably not particularly meaningful since only the first two terms of the Low expansion are known, and these depend also on the on-shell amplitudes and on kinematic coefficients which can vary radically with the geometry, thus hiding the dependence on any natural expansion parameter k/E_0 . In a *qualitative* sense, however, for any E_0 kinematic conditions which give k/E_0 large are clearly better than those with k/E_0 small. Thus k/E_0 remains a useful qualitative parameter for assessing the merit of various geometries.

What has not been fully realized is that *both* parameters Δm^2 and k/E_0 should be large and that different geometries emphasize one or the other. This can be seen in Fig. 2 which shows the kinematic regions of existing and of some possible experiments in the Δm^2 versus $(k/T_1)_{LAB}$ plane. (Replacing $T_1 \rightarrow T_{ave}$ gives qualitatively the same results.) The TRIUMF and Manitoba experiments, in which both proton angles (θ_3, θ_4) were fixed, obtain significantly larger k/T_1 than the UCLA experiment in which θ_3 and θ_4 were fixed. However, the higher energy of the UCLA experiment allows larger Δm^2 to be reached. For fixed geometry (e.g. $\theta_3 = \theta_4 = 18^\circ$) increasing the incident energy increases the value of Δm^2 obtained without much change in k/T_1 , which is large over the entire

accessible region. Highly non-coplanar geometries, as required for measurement of the "forbidden" asymmetries, give relatively large Δm^2 for a given energy but at some loss in k/T_1 . For the same angles, the (θ_3, θ_4) fixed geometry reaches about the same maximum Δm^2 and k/T_1 as does the (θ_3, θ_4) fixed geometry, but the allowed region ranges down to $k/T_1 = \Delta m^2 = 0$. Thus a large portion of the data in this geometry falls in the uninteresting soft-photon region.

It is perhaps more physical to treat the parameter k/E_0 in the centre-of-mass system, thus avoiding distortions in the magnitude of k caused by the transformation of the lab system. Then in a plot of Δm^2 versus $(k/T)_{c.m.}$, all experiments at a given energy fall on a line through the origin whose slope increases with increasing energy. To distinguish among different geometries at a fixed energy one can define an efficiency parameter ϵ which indicates how far out along the line a given experiment is via $\epsilon = \Delta m^2 / (\Delta m^2)_{\max} \equiv k c.m. / (k c.m.)_{\max} \equiv (s_1 - s_f) / (s_1 - 4m^2)$ with $(\Delta m^2)_{\max} = (s_1 - 4m^2) / 2m^2$, $s_1 = (p_1' + p_2')^2$ and $s_f = (p_3' + p_4')^2$. In terms of this parameter the (θ_3, θ_4) fixed geometry is more efficient than the (θ_3, θ_4) one since its average ϵ is greater, though the maximum ϵ obtained is similar for the same angles. Thus $(\Delta m^2)_{\max}$, which is fixed by the incident energy, indicates the maximum distance off shell possible whereas ϵ measures the success of a particular geometry in reaching that maximum.

So far non-soft-photon effects have apparently been seen² to the right of the dashed line in Fig. 2 and perhaps at the end points in the TRIUMF experiment.¹ Thus new experiments should be performed in the Δm^2 , k/T_1 regions larger than these. The 450 MeV geometries shown are examples of experiments in regions easily accessible at machines such as TRIUMF which would achieve larger Δm^2 and k/T_1 than ever before obtained. The

non-coplanar example would be particularly appropriate for investigating the "forbidden" asymmetries discussed above. In such a geometry the photon is severely restricted in its direction and so could perhaps be detected in coincidence with the two protons without much loss of efficiency, thus improving background rejection.

At lower energies Δm^2 , and thus off-shell effects, would be expected to be much smaller. However, extremely accurate experiments could perhaps offset this disadvantage and still obtain useful information provided that the theoretical interpretation can also be made equally accurately. In general it would seem simpler to try to find regions where the effects are larger and thus where small ambiguities in the theory would be less important.

Finally, it should be emphasized that while kinematic arguments of the type given here can be very useful and suggestive they are not definitive. It is fairly clear that Δm^2 and k/E_0 large in some sense are necessary to see interesting off-shell effects, but since the coefficients in the Low expansion depend on geometry it is not clear that large values are sufficient. One must eventually do model calculations in models which allow variation of off-shell information while holding on-shell information constant.

The author would like to acknowledge conversations with Dr. L. Heller, who independently observed the suppression of A_1 by one power of k , with Drs. J. Rogers, J. Jovanovich, and with theoretical colleagues at TRIUMF. This work was supported in part by the National Research Council of Canada.

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Figure Captions

1. ppv asymmetry for initially polarized beam. $A_{y\text{-elastic}}$ is the transverse asymmetry for elastic pp scattering evaluated at the energy and momentum transfer used for the on-shell information in the SPA.
2. Kinematic regions in a plot of off-shell parameter Δm^2 vs soft-photon parameter $(k/T_1)_{\text{LAB}}$ sampled by existing and several proposed experiments. Non-soft-photon effects appear in the UCLA experiment to the right of the dashed line and perhaps at the end points of the TRIUMF experiment.

Fig. 1

Fig. 2