Proton-proton bremsstrahlung and elastic nucleon-nucleon scattering
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Bremsstrahlung and the low energy $NN$ interaction

In Chapter 2 the main ingredients of the microscopic model for $pp\gamma$ have been presented and, together with the microscopic model of Nakayama et al. and the soft-photon model of Korchin and Scholten, its predictions have been compared with a representative sample of the high accuracy KVI $pp\gamma$ experimental data. For certain asymmetric proton angles a large discrepancy between the microscopical calculations and the experimental data has been observed. Two possible sources for the observed discrepancy have been mentioned: the sensitivity to the on-shell nucleon-nucleon interaction and Coulomb corrections.

The detailed investigation of these two possible sources for discrepancy is the subject of this chapter. The focus will be on the Martinus model and to try to improve its predictions. The sensitivity on the on-shell nucleon-nucleon interaction is studied at the level of individual $NN$ partial waves. Coulomb corrections are expected to be relevant only when the low-energy nucleon-nucleon interaction enters the calculations. As a consequence, in Chapter 3 a non-relativistic toy model for bremsstrahlung that accounts for the Coulomb interaction only in the $^1S_0$ channel has been built. It will be used here to decide to what extent Coulomb corrections are relevant for the kinematical situations covered by the KVI $pp\gamma$ experiment.

4.1 Analysis of the discrepancy

In Fig. (2.4) and Fig. (2.5) the cross-section predictions of the relativistic model of Martinus for a few kinematical regions, as a function of the angle of the emitted photon ($\theta_\gamma$) or of one the outgoing protons ($\theta_{1,2}$) have been plotted. For comparison, the experimental results of the KVI experiment [58], performed at a proton energy of 190 MeV, are shown. For four of the presented kinematics (namely $\theta_1=8^\circ - \theta_2=16^\circ$, $\theta_1=8^\circ - \theta_2=19^\circ$, $\theta_2=16^\circ - \theta_\gamma=145^\circ$ and $\theta_1=8^\circ - \theta_\gamma=145^\circ$) a large discrepancy between theory and experiment is observed. In each case the discrepancy appears at angles where the cross section has a peak. The same type of discrepancy is present also for other kinematics of the KVI experiment, which are not presented here. Still, for a number of kinematical regions theory and experimental data are in reasonable agreement: two such cases have been presented in Chapter 2: $\theta_1=16^\circ - \theta_\gamma=145^\circ$ and $\theta_1=16^\circ - \theta_2=19^\circ$). The size of the discrepancy is disturbing, since the ingredients that go into the computation of the bremsstrahlung amplitude ($NN$ interaction, $NN\gamma$ vertex) are thought to be well
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Figure 4.1: The effect of the negative-energy states on the bremsstrahlung cross section is illustrated for two kinematics at $T_{lab}=190$ MeV for $\theta_1 = 8^\circ$, $\theta_2 = 16^\circ$ and $\theta_1 = 16^\circ$, $\theta_2 = 19^\circ$. Calculations including both the negative- and positive-energy states (+/−) or only the positive-energy states (+) are shown. Only calculations including the impulse approximation (IA) or the nucleonic (IA+ rescattering) contributions have been considered. It is seen that the full calculation with only positive-energy states included is close to the full calculation with both positive- and negative-energy states included, in agreement with the soft-photon theorem for bremsstrahlung.

Table 4.1: Cross sections, in $\mu$b/sr/$\text{rad}^2$, for different kinematics $\theta_1$, $\theta_2$, $\theta_\gamma$, split up in partial waves, radiation from initial and final proton legs, and the total; only contributions from the positive-energy states have been considered. The results of the last four rows of the table are obtained by considering all the partial waves up to $J = 2$ together. The kinematics correspond to the backward peak in the cross section. Similar results are found for different values of $\theta_\gamma$, while keeping $\theta_1$ and $\theta_2$ fixed.
4.1. Analysis of the discrepancy

As already mentioned, various contributions have been considered in the Martinus et al. model for bremsstrahlung: nucleonic (impulse approximation and rescattering diagrams), meson-exchange currents (MEC) and $\Delta$-isobar contributions. We note that it is unlikely that the discrepancy is due to a poor description of the MEC and $\Delta$-isobar terms, since their contributions for the kinematics studied here is small, especially at the position of the cross-section peaks (see Fig. (2.4) and Fig. (2.5)). We will thus concentrate on the nucleonic terms. The contribution of the rescattering diagram is important (Fig. (4.1)) giving a sizable decrease of the cross section, with respect to the IA result, when both the positive- and negative-energy states are considered. The main part of its contribution comes from coupling to the negative-energy states, the positive-energy state contribution is modest (compare the dashed and the dash-dotted curves). Negative-energy states contributions from the IA diagrams and from the rescattering diagram cancel each other to a large extent as can be seen from Fig. (4.1). This has been shown to hold up to photon energies of about 100 MeV [52]. The cancellation becomes exact in the limit of photon energy going to zero, as required by the soft-photon theorem for bremsstrahlung [80]. Keeping only the positive-energy states is thus a good approximation to the full nucleonic result. We conclude that the mentioned discrepancy already resides at the level of IA diagrams. For the IA diagrams we have determined contributions of the different partial waves separately. This allows us to understand the difference between kinematical regions like $\theta_1=8^\circ$, $\theta_2=16^\circ$ and $\theta_1=16^\circ$, $\theta_2=19^\circ$ in order to discover the possible source of these discrepancies. The results for the first few $NN$ partial waves contributing to $pp\gamma$, at the region of the cross section peaks, are shown in Table (4.1). From this table it is clear that for the specific kinematics we have chosen, only a few partial waves are important for bremsstrahlung: $^1S_0$, $^3P_1$ and $^3P_2$.

A further insight is obtained once the kinematics of the six cases are analyzed. There are two distinct energy values at which the elastic T-matrix is evaluated: one is the kinetic energy of the projectile proton (in the case of the final-state bremsstrahlung), and the
other one is the kinetic energy of the outgoing proton (initial-state bremsstrahlung). The latter can be very low, since the emitted photons are energetic. For the rescattering diagram, both cases occur, since the elastic T-matrix is evaluated at high energy before emission and at low energy after emission. In Fig. (4.2), the energy ($T_{lab} = [(E_1' + E_2')^2 - (\vec{p}_1' + \vec{p}_2')^2]/2M - 2M$) at which the elastic $NN$ T-matrix is evaluated is plotted as a function of the unspecified proton angle ($\theta_1$ or $\theta_2$) (left panel), and as a function of the photon angle (right panel). The two panels correspond to the kinematics presented in Fig. (1.4-5). It is seen that the kinematical points in disagreement with the experiment correspond to those for which the elastic T-matrix is evaluated at low energies (of the order of 10 MeV). The lowest energies correspond to the cross-section peaks. For the $\theta_1=16^\circ$, $\theta_2=19^\circ$ and $\theta_1=15^\circ$, $\theta_2=19^\circ$ cases the elastic T-matrix is evaluated at energies above 25 MeV at the points where experimental data exist.

In Fig. (4.3) we have plotted the difference between the theoretical and experimental values of the differential cross section as a function of the kinetic energy of the outgoing protons $T_{lab}$ for the six kinematical cases presented here. It supports the previous conclusion that there is a systematic large discrepancy between the theory and experiment for the cases for which the energy of the outgoing proton system is less than 15 MeV. A similar figure, with data points for other kinematical regions, has been presented in [81]. An increase of the discrepancy with the decrease of the kinetic energy $T_{rel}$ is seen. There are a few data points which do not follow the general trend: first, a few BLOCK data (depicted by triangles) at low outgoing energy ($\approx 16$ MeV) which belong to the $\theta_1=8^\circ$ - $\theta_2=19^\circ$ for $\theta_\gamma$ close to 90$^\circ$ and a SUPERCLUSTER point (squares) that even though at relatively high outgoing energy (38 MeV) deviates significantly from theory. This last
point belongs to the $\theta_1=8^\circ - \theta_\gamma=145^\circ$ kinematics (see Fig. (2.5)) for which which the discrepancy extends outside the peak.

The above considerations lead us to the conclusion that a significant discrepancy is present for the kinematics for which the final $pp$ system has a low kinetic energy. We note that in both the single-scattering diagrams and the rescattering diagram the elastic T-matrix enters, evaluated at this low energy. It is thus plausible that part of the problem resides in a poor description of the elastic T-matrix at low energies, and since at low energies most of the interaction goes via the $^1S_0$ channel, we conclude that this partial wave is at the origin of most of the observed discrepancy. For both cases presented in Table (4.1) $^3P$ waves are important: for the $\theta_1=8^\circ, \theta_2=16^\circ$ case they are somewhat less important then the $^1S_0$ partial wave, while for the $\theta_1=16^\circ, \theta_2=19^\circ$ kinematics their contribution is dominant. Important contributions of the $^3P$ waves arise in diagrams in which the elastic T-matrix is evaluated at high energies. For an accurate description of bremsstrahlung, it is thus necessary that the $^3P$ waves are accurately reproduced by the OBE model we use at an energy equal to that of the incoming proton. But, since kinematics dominated by $^3P$ waves are in good agreement with the experiment (suggesting a reasonable description of these partial waves), we will concentrate on the $^1S_0$ partial wave contributions to the $NN$ potential.

Having concluded that problems occur once the elastic T-matrix is evaluated at low energies a natural question rises. It is well known that in this region the Coulomb interaction has to be taken into account. The cross section for pure Coulomb bremsstrahlung has been shown to be small (of the order of nanobarns) [71], and thus it will be of no practical importance to consider it. Still, the Coulomb corrections to the strong bremsstrahlung amplitude might be important. Including them in a relativistic model is difficult due to the long-range nature of the Coulomb interaction. We will rely on the non-relativistic toy model developed in Chapter 3 to pass an opinion about the importance of these corrections.

### 4.2 Coulomb correction to $pp\gamma$ at 190 MeV

The influence of the Coulomb interaction on the $pp\gamma$ cross section has been studied before [71, 99, 119]. Large effects have been reported for the case of small symmetric outgoing proton angles ($\theta_1 = \theta_2$) and low energy of the incoming protons [71]. This is due to the fact that for this particular case the elastic T-matrix is probed at low energy, case for which the Coulomb corrections are large (see Fig. (3.5)). Our result in Chapter 3, Fig. (3.7) and Fig. (3.8), which served as a check for the toy model, agrees with these results. For energies of the projectile proton higher than 100 MeV the effect of including the Coulomb interaction was shown to be small (of the order of a few percent), for certain kinematics with symmetric outgoing protons.

Our findings are consistent with the above mentioned results, as can be seen from Fig. (4.4). There we present the effect of the Coulomb interaction on the differential cross-section for the two kinematics already discussed in the previous sections. It is seen that the effect of Coulomb is indeed small and it amounts to at most 1% of the total cross section for the separable-potential model. In this case the result with and without
Coulomb corrections to the \( pp\gamma \) at \( T_{lab}=190 \) MeV for the six KVI kinematics discussed in the text. Separable potential calculations are denoted by the dotted (no Coulomb) and full (Coulomb included) curves. The corresponding calculations that make use of the EFT model for the \( NN \) interaction are plotted by the dashed and dashed-dotted curves respectively. Coulomb are practically indistinguishable on the scale shown in Fig. (4.4). For a few angles a small increase of the cross-section is observed once the Coulomb interaction is included. Nevertheless, this result is consistent with zero increase or decrease if one take into account the numerical error, which amounts to about 0.5%. In the case of the \( pp\gamma \) model with the \( NN \) interaction based on the EFT model with \( \mu=0.7 \) fm\(^{-1} \) (see Fig. (3.4)) the effect of the Coulomb interaction is clearly visible at the peaks of the cross section, but the observed decrease never amounts to more than 2-3% of the total result.

Coulomb corrections to the bremsstrahlung cross section can be important even for the case of a projectile proton with kinetic energy \( T_{lab}=190 \) MeV if the energy of the outgoing protons is very small. Two such situation are presented in Fig. (4.5). The amount of the Coulomb correction varies rapidly as a function of the varied angle (\( \theta_\gamma \) or \( \theta_1 \) in this case) from about 25% at the peak to less than 1% a few degrees away. This
4.2. Coulomb correction to $pp\gamma$ at 190 MeV

Figure 4.5: The same as in Fig. (4.4) but the two kinematics shown here illustrate that Coulomb effects become very important once the outgoing proton angle become very small. Such kinematical regions have not been probed during the KVI experiment.

is due to a rapid variation of the kinetic energy of the outgoing protons from 0.76 MeV, 1.39 MeV and 1.32 MeV for the three peaks respectively (from left to right) to about 20 MeV over a range of a few degrees. This type of kinematical regions has not been probed by the KVI experiment, where the lowest value of the energy of the outgoing protons was around 10 MeV. Such a kinematics has been probed by the IUCF experiment [120] at 294 MeV with $\theta_1=\theta_2=8.4^\circ$. It has been shown in Ref. [118] that the inclusion of the Coulomb corrections is essential for a close reproduction of the experimental result.

Coulomb effects in the higher partial waves are thought to be negligible. This is due to the fact that higher partial waves contributions enter via terms evaluated at high energies. In the presented kinematical situations, a full calculation of the Coulomb effects (including the higher partial waves) will not reveal a bigger effect than the one already observed for the $^1S_0$ wave, which was at most 1%. We conclude that in the kinematical regions probed by the KVI experiment the Coulomb corrections are not important, excluding them as a possible source for the observed discrepancy between the

Table 4.2: The origin of the Coulomb corrections can be revealed by setting $\alpha = 0$ in the Coulomb-corrected elastic T-matrix ($T^{\text{SC}}$) and in the two-body operator ($J$) in Eq. (3.71) and Eq. (3.72) alternatively. Results for no Coulomb corrections at all ($\alpha = 0$) and the full result ($\alpha = 1/137$) are also presented.

<table>
<thead>
<tr>
<th>$\theta_1$</th>
<th>$\theta_2$</th>
<th>$\theta_\gamma$</th>
<th>$\alpha=0$</th>
<th>$\alpha=1/137$</th>
<th>$T^{\text{SC}}(\alpha = 0)$</th>
<th>$J(\alpha = 0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^\circ$</td>
<td>$7^\circ$</td>
<td>$150^\circ$</td>
<td>8.3665</td>
<td>6.5480</td>
<td>7.9101</td>
<td>6.9462</td>
</tr>
<tr>
<td>$8^\circ$</td>
<td>$16^\circ$</td>
<td>$130^\circ$</td>
<td>0.8958</td>
<td>0.8870</td>
<td>0.8525</td>
<td>0.9323</td>
</tr>
</tbody>
</table>
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Figure 4.6: Bremsstrahlung cross sections at $T_{lab}=190$ MeV incoming proton kinetic energy for two different kinematics: $\theta_1=8^\circ$, $\theta_2=16^\circ$ and $\theta_1=16^\circ$, $\theta_2=19^\circ$ as a function of $\theta_\gamma$. In the OBE model the $^1S_0$ partial wave has been replaced with the one obtained from the separable potential, resulting in the dotted curve, to be compared with the original OBE result (the full line).

model and the data.

From the expressions of the external-legs contributions to bremsstrahlung, it can be seen that the Coulomb corrections can appear in two places: the half off-shell elastic T-matrix ($T^{SC}$) and the two-body operator (propagator plus the electromagnetic vertex $\langle \Psi(\pm)|H_{em}|\Psi(\pm)\rangle$) as can be seen from Eq. (3.71) and Eq. (3.72). One can study in which of the two terms the Coulomb corrections are bigger. For that one can switch off, alternatively, the Coulomb corrections in the elastic T-matrix and in the two-body operator. The results are presented in the Table (4.2) for the following two kinematics: $\theta_1=1^\circ$, $\theta_2=7^\circ$, $\theta_\gamma=150^\circ$ and $\theta_1=8^\circ$, $\theta_2=16^\circ$, $\theta_\gamma=130^\circ$. The effects of the Coulomb corrections in the elastic T-matrix (the column denoted by $J(\alpha=0)$) and in the two-body operator (the $T_{el}(\alpha=0)$ column) seem to have opposite effects: Coulomb effects in the elastic T-matrix alone seem to lower the cross section for the first kinematics while it seems to increase it for the second. Coulomb effects in the two-body operator alone decrease the cross section in both cases, but much more than in the full result. One concludes that both ingredients are necessary if the Coulomb effect on bremsstrahlung is to be described accurately.

4.3 On-shell sensitivity of $pp\gamma$

In order to study the effect of the separable $^1S_0$ potentials on the $pp\gamma$ cross section in a realistic model we have modified the OBE model of Fleischer and Tjon. We have discarded any contributions from the negative-energy states, since when properly treated their effect on the bremsstrahlung cross section at 190 MeV is small [52, 65]. Furthermore we have only kept partial waves up to a total angular momentum $J=2$. Contributions
of higher partial waves, although not explicitly shown here, are small. We have, however, replaced the $^1S_0$ partial wave amplitude with the one given by the separable $pp$ potential derived in Chapter 3. The consequences of considering such a potential, for $pp$ bremsstrahlung, are shown in Fig. (4.6). Calculations were performed using the Martinus et al. model for bremsstrahlung. This calculation adds to the results from Fig. (4.4), since contributions from partial waves are included here as well. For the kinematics for which we have shown that the $^1S_0$ partial wave is dominant, some differences with respect to the original OBE model are observed. We conclude that an accurate description of the $^1S_0$ wave is important for an accurate description of bremsstrahlung.

The observed discrepancy was shown to appear in kinematical regions where the $pp\gamma$ amplitude is dominated by contributions from the $^1S_0$ partial wave. Two possible sources for this inaccuracy were identified: the difference between a $pp$ and a $np$ potential in this region and Coulomb corrections to the elastic T-matrix. Regarding the interference of the strong and Coulomb interaction, we have shown in the previous section that the difference between the pure strong bremsstrahlung and the Coulomb-modified strong bremsstrahlung is of the order of 1% at the peaks of the cross section for kinematics.
specific to the KVI experiment. One concludes that at least part of the discrepancy has its origin in the fact that originally the strong interaction was fitted to a potential with a scattering length $a = -23.7$ fm, which corresponds to a $np$ system. Given the fact that for the KVI kinematics the Coulomb corrections are small a fit of the strong interaction which would give $a = -17.1$ fm should be performed, since the OBE model does not incorporate the Coulomb interaction explicitly. Such a fit is performed by fitting the phase shifts of the model in question to the experimentally available ones. Extracting such phase shifts from the $pp$ ones is model dependent. Lacking a model which incorporates both the Coulomb interaction and the relativistic OBE $NN$ interaction, we have performed a fit of the relativistic OBE model of Fleischer and Tjon to the $pp$ phase shifts of the PWA93 [20, 121, 122] analysis. The range of the fit was from 5 to 215 MeV, the lower limit has been chosen having in mind that below this energy Coulomb effects will grow in magnitude and a fit of the OBE model to reproduce Coulomb effects will be less trustworthy as the energy decreases.

In Fig. (4.7) we compare the $pp$ strong phase shifts of the Nijmegen PWA93 and those given by the Fleischer-Tjon OBE model before and after refitting. The new coupling constants for the OBE model are presented in the Table (4.3). For comparison also the coupling constants before the refit are shown. Most of the partial waves have been improved by the process of refitting. One observes a substantial improvement of the $^1S_0$ phase shift, which now lies very close to the experimental strong $pp$ phase shift in the 5-215 MeV range (shown only up to 50 MeV in the figure). The $^3P_0$ and $^3P_2$ also show a noticeable improvement, being now close to the experimental data also in the high-energy region. An exception to the general trend of improvement is the $^3P_1$ wave which is still off in the high-energy region. In one of the previous sections, this partial wave was seen to give an important contribution (25-30 %) to the cross section even for kinematics dominated by the $^1S_0$ wave.

A possible residual on-shell dependence has been investigated by modifying the elastic T-matrix as to reproduce the PWA results exactly and investigating how this modifies the bremsstrahlung cross section for various kinematics. Using the results of the PWA93 [121] analysis for the $pp$ phase shifts the Coulomb-corrected matrix elements in the partial-wave basis for each value of the total angular momentum $J$ have been computed [123]. The partial-wave amplitudes of the OBE model have then been normalized on-shell to these experimental values (in the expression below, momenta with a hat are on-shell, while the others can also be off-shell),

$$T(\hat{p}, k) = T^{(PWA)}(\hat{p}, \hat{p}) \cdot \frac{T^{(OBE)}(\hat{p}, k)}{T^{(OBE)}(\hat{p}, \hat{p})}.$$  (4.1)
4.3. On-shell sensitivity of $pp\gamma$

$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 d\gamma} (\text{mb sterad}^2)$

\[\begin{array}{cccc}
\theta_1=8^\circ, \theta_2=16^\circ & \theta_1=16^\circ, \theta_2=19^\circ \\
0 & 0 & 0 & 0 \\
1 & 1 & 2 & 2 \\
2 & 2 & 3 & 3 \\
\end{array}\]

**Figure 4.8:** Bremsstrahlung cross sections at $T_{lab}=190$ MeV incoming proton kinetic energy for two different kinematics: $\theta_1=8^\circ, \theta_2=16^\circ$ and $\theta_1=16^\circ, \theta_2=19^\circ$ as a function of $\theta_\gamma$. Calculations have been performed by using the OBE model (full line) with contributions only from the positive energy states and the OBE model normalized on-shell to the PWA data (dotted and dashed lines). The full and the dotted lines fall almost on top of each other.

**Table 4.4:** Comparison of the partial-wave contributions to the IA graphs as computed with the refitted or the on-shell normalized potential.

<table>
<thead>
<tr>
<th></th>
<th>$\theta_1$, $\theta_2$, $\theta_\gamma$</th>
<th>$8^\circ$, $16^\circ$, $139.5^\circ$</th>
<th>$16^\circ$, $19^\circ$, $159.3^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>new fit</td>
<td>normalized</td>
<td>new fit</td>
</tr>
<tr>
<td>$^1S_0$</td>
<td>1.513</td>
<td>1.507</td>
<td>0.379</td>
</tr>
<tr>
<td>$^3P_0$</td>
<td>0.024</td>
<td>0.022</td>
<td>0.024</td>
</tr>
<tr>
<td>$^3P_1$</td>
<td>0.114</td>
<td>0.129</td>
<td>0.167</td>
</tr>
<tr>
<td>$^3P_2$</td>
<td>0.378</td>
<td>0.423</td>
<td>0.513</td>
</tr>
<tr>
<td>$^1D_2$</td>
<td>0.003</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>IA</td>
<td>2.207</td>
<td>2.242</td>
<td>1.514</td>
</tr>
</tbody>
</table>

This ensures that on-shell the elastic experimental data are reproduced, while keeping the off-shell structure of the elastic T-matrix as dictated by the OBE model. Again, we have produced two such modifications to the initial OBE model: in the first only the $^1S_0$ partial wave has been modified in the described way, while for the second case all partial waves were subject to this modification. Bremsstrahlung has been computed by considering only the IA graphs. Partial waves with an total angular momentum higher then 2 have also been omitted.

The results are shown in Fig. (4.8). The case when only the $^1S_0$ wave is modified (dotted line) hardly differs from the refitted OBE calculation, suggesting that now the low-energy behavior of the $pp$ potential is properly reproduced. When all partial waves
Figure 4.9: Cross sections and analyzing powers for bremsstrahlung at $T_{lab}=190$ MeV for the four kinematics discussed in the text. Full line represents the old calculation while the dashed one represents the calculation using the new potential. Both calculation were done considering the full model of Martinus et al. for bremsstrahlung. As usual, the experimental data are from the KVI experiment.

Figure 4.10: The same as in Fig. (4.9) but for different kinematics
are normalized (dashed line) a slight increase in the cross section is observed for both cases presented, with a stronger increase for the $P$ wave dominated kinematics. This is due to the fact, that after the refit the $P$ waves phase shifts still deviate at high energies from the experimental ones, the on-shell normalization causing the elastic T-matrix in these channels to increase towards the experimental data. In Table (4.4) we have listed the various partial-wave contributions to the IA graphs both before and after the on-shell normalization has been performed. Each of the $^3P_1$ and $^3P_2$ partial wave contributions suffer changes of the order of 10-15%, but when all partial waves are considered together the change is at most 5%. We conclude that after the new fit has been performed there is still a sensitivity to the on-shell $NN$ interaction, which might trigger a change of at most 5% in the bremsstrahlung cross section once a perfect fit to the elastic $NN$ scattering data would be obtained.

To conclude we present the cross section and analyzing-power predictions for the new fit. The full $pp\gamma$ model is used, contributions from the negative-energy states and two-body currents being thus included. From Fig. (4.9) and Fig. (4.10) it is seen that the cross-section predictions for the $\theta_2=16^\circ - \theta_\gamma=145^\circ$, $\theta_1=8^\circ - \theta_\gamma=145^\circ$, $\theta_1=8^\circ - \theta_2=16^\circ$ and $\theta_1=8^\circ - \theta_2=19^\circ$ are improved by the new fit. A decrease of the discrepancy has been achieved by improving the low-energy part of the strong interaction, but a sizable discrepancy remains. Turning our attention to the analyzing powers, we notice that the new fit somewhat improves the predicted values with respect to the experimental data, especially for the $\theta_2=16^\circ$, $\theta_\gamma=145^\circ$ and $\theta_1=16^\circ$, $\theta_\gamma=145^\circ$. The overall agreement with the experimental data remains satisfactory, also due to the fact the experimental values of this observable carry rather large error bars.

4.4 Summary

We have demonstrated the sensitivity of the bremsstrahlung observables to the low-energy $NN$ interaction. The $pp\gamma$ cross section at 190 MeV varies strongly throughout the allowed phase space, the maxima corresponding to situations when the elastic $NN$ T-matrix is evaluated at very low energies. In the cases dominated by the $^1S_0$ partial wave a significant discrepancy between theory and experiment has been observed previously. It was shown here that an important part of it originates in a poor description of the $NN$ interaction at low energies (the $^1S_0$ channel). For the kinematics discussed here the corrections due to the Coulomb interaction were shown to be minor. The $NN$ potential was improved by a refit of the Fleischer-Tjon potential to the $pp$ phase shifts in the 5-215 MeV region. This resulted in an improved $^1S_0$ phase shift (especially in the low-energy region), along with other phase shifts. The analyzing powers have been improved somewhat due to the refit of the $NN$ interaction, their rather good agreement with the experimental data still holding. Using the refitted potential an improvement in the description of the bremsstrahlung cross sections is observed. This improvement is mainly due to the change of the scattering length from the value of an $np$ system towards the value of the $pp$ system. Still a sizable discrepancy, of unclear origin, persists even after the refit.
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