Helicity Correlated Time Shift and the Asymmetry in G0

Jianglai Liu and Betsy Beise
Dept. of Physics, Univ. of Maryland College Park, MD 20742
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Motivation

In the forward angle mode of the G0 experiment, we measure the asymmetry in the proton yield from electron-proton elastic scattering. The asymmetry is $A = (Y1 - Y2)/(Y1 + Y2)$ where Y1 and Y2 are the yields in each helicity state, respectively. The G0 data analysis software reconstructs the time of flight spectra using a time window for the elastic protons, integrates the yield over the time window to get the yields within the time windows for each helicity, and then calculates the above asymmetry. If there is a helicity correlated shift in the arrival time of the beam, the protons of one helicity will arrive some time later in the time window than the those with the other helicity, and a false asymmetry can be introduced. The purpose of this work is to examine how much helicity dependent time shift can be tolerated in the measured asymmetry, requiring that any change in the calculated asymmetry be small compared to the statistical error of a 40 day run.

Simulation

For a 40-day running period, the elastic proton yield in a single detector is roughly $40 \times 24 \times 3600 \times 10^6 \times 0.7 = 2.4 \times 10^{12}$. The data rate assumed for each detector is about 1 MHz, and the 0.7 assumes the elastic proton events are 70% of the total yield, based on the simulation by G. Batigne, *et al.*, in G0-00-048. The statistical error on the resulting asymmetry is $\Delta A = 1/\sqrt{2Y}$ where Y is the yield for one helicity state. Therefore, the statistical uncertainty we have on the asymmetry is 0.64 ppm. For the Q^2 G0 proposed, $1.0(GeV/C)^2$, we assumed the physical asymmetry is about -20 ppm, resulting in a relative statistical error of 3-4%.

To simulate the effect of a helicity correlated time shift, we used the mock data generation code to generate helicity correlated TOF distributions consistent with a -20 ppm asymmetry, in bin sizes of either the 0.25 ns or 1 ns, corresponding to the French and NA electronics, respectively. For each detector, we generated the two spectra with the appropriate statistics of a 40 day run. Then by analyzing the output TOF spectra, we tried to see whether we could successfully reproduce the input asymmetry.

To generate the TOF distributions, we started with the TOF simulated from GEANT by Batigne *et al.*. The pion peak is well-separated from the elastic protons, and there is a low random background arising from neutrons. The inelastic proton peak height is about 10% of the elastic protons on most detectors, with their centers separated by about 5 ns. The elastic proton peak has a width (1σ) of about 1 ns. The inelastic proton peak is broader, around 2.5 ns in width. Fig. [1] shows a typical TOF histogram we constructed for the NA electronics according to Guillaume's report (one helicity state only). The small bump adjacent to the elastic proton peak is due to inelastic protons. The bin weights of the histogram are normalized to a yield corresponding to a 40 day run.

Asymmetry Results

We first considered the "cleanest" case, assuming no background. One has two well-separated peaks in the spectra and a false asymmetry is introduced only by the time shift. We set identical time windows for the spectra of both helicities. The number of counts in each spectrum was integrated and subtracted one from the other in order to calculate an asymmetry: this was performed with and without a helicity correlated time shift. Figs. [2] and [4] show the results for French and American electronics bin width (0.25 ns/bin and 1.0 ns/bin respectively) for an integration window of $\pm 1\sigma$ of the peak. (The range is actually $2\sigma + 1$ bin. We first find the central bin and integrate to 1σ on both sides of it.) The horizontal axis is the time shift and the vertical axis is the relative difference between the extracted asymmetry and the real asymmetry that we put into the simulation. One can see from the results, as expected, that the finer French binning will tolerate a larger helicity correlated time shift than the American binning. The error in the extracted asymmetry for American binning falls becomes 10% when the time shift is 4×10^{-5} ns while the error in the asymmetry calculated with the French binning reaches 10% at 1×10^{-4} ns.

The false asymmetry is introduced by the fact that once the peak shifts relative to the time window, the yield that enters the time window is not equal to the yield that leaves it. This effect is minimized if the bin height on both ends of the window are equal. For a symmetric peak (which could be possible in the real experiment) this simply means that the tolerance on the time shift depends on how well the time window is centered relative to the peak, or how well the the peak is centered in the window. Note that the asymmetric appearance of a peak in the TOF spectrum, as in Fig. [1], is mostly caused by the asymmetric binning rather than a physically asymmetric shape. The French binning has better resolution to center the time window and is thus less sensitive to helicity correlated time shifts. We also tried $\pm 2\sigma$ integration on both bin types and the situation improved as expected, shown in Figs. [3] and [5].

The resulting false asymmetry was also calculated analytically, based on two Gaussian functions, differing only by an asymmetry in heights and a shift of the centers. (The analytic expression involves some error functions and is not very illuminating.) The Gaussian parameters were similar to the ones used in the simulation and the asymmetry was -20 ppm. We first assumed the time window was $\pm 1\sigma$. Without any time shift between the two, we obviously got the correct asymmetry back by integrating the two spectra within the time window. Then we shifted the time and calculated the asymmetry again, and so forth. The results are in Fig. [6]. The vertical axis on the plot is the relative difference between the extracted and real asymmetry and the horizontal axis is the time shift. Statistical error bars were assigned according to the yields from the integration. In this case, only when the shift exceeds 2×10^{-3} ns does the false asymmetry become larger than the statistical uncertainty. Then we made the time window off-center (as if we had shifted the peak), $[-1.5\sigma, 0.5\sigma]$ relative to the center of the Gaussian, and did the calculation again. The results (see Fig. [7]) follow the argument as above. Note that this would be the worst possible situation one could get if the bin width is $\pm 1\sigma$. It corresponds to the picture that two bins in the center have the same yield, so that one could assign the central bin to either of the two and mistake the real center of the peak by 0.5σ. (Of course a smarter choice would be to take the average position of the two bins as the center and do the integral on both sides in order to get a more symmetric yield. Here, we are just trying to demonstrate an extreme situation.) The tolerance becomes much lower. At this point, if we widen the window by a factor of 2, $[-2.5\sigma, 1.5\sigma]$, the situation is remedied as shown in Fig. [8].

One obvious way to correct the false asymmetry introduced by the time shift is by doing the fit. We did the Gaussian fit on the spectra. We computed the areas under the Gaussians according to the fit parameters and treated them as the proton yields. The errors of the fit propagating into the asymmetry results were found to be within several percent level. The asymmetry found by this way was fairly stable (independent of the time shift). However, this method is less likely to be adopted in the real experiment since the peaks might not have a well-behaved shape.

Since G0 detector covers a range of Q^2, from $0.12(GeV/C)^2$ to $1.0(GeV/C)^2$, the expected asymmetry also varies. In fact, -20 ppm asymmetry roughly corresponds to the highest Q^2, $1.0(GeV/C)^2$. We carried out the similar study on two other asymmetry values, -2 ppm and -10 ppm. We assumed the maximum time shift that could be tolerated corresponded to 5% false asymmetry. Then the time shift values were found to be proportional to the asymmetry. This result is not surprising. Mathematically, for small time shift as we encounter here, the introduced false asymmetry is approximately linear with the shift. If the maximum false asymmetry is defined in terms of a fixed percentage of the asymmetry, then the time shift corresponding to it would also be linear with the asymmetry.

A flat background was also added to the TOF spectra, with a different asymmetry, -50 ppm, assumed for the background. The way we calculated asymmetry in this case was to make a time window of the same width at some "remote" region of the spectrum, *i.e.* no overlap with both proton and pion peaks, take the yield within it, subtract this from the yield within the elastic proton window and get the net yield. The behavior we found on the asymmetry was almost the same as if there were no background present (the first situation discussed).

Then we added the inelastic proton peak in the TOF spectra. For simplicity, we assumed Gaussian shapes on both elastic and inelastic proton peaks. The positions, heights and the widths were taken roughly in accord with the simulation of Guillaume Batigne. Since we don't have any idea about the asymmetry associated with the inelastic protons, it is desirable that it not contaminate the elastic protons. One possibility would be to fit the background for each spectra and subtract them to get elastic yields. We tried this scenario, again assuming that the elastic asymmetry was -20 ppm, and we used 40 ppm as the inelastic proton asymmetry. The results are shown in Figs. [9] and [10] for French and NA binning respectively. The error bars on the plots are the sum of the statistical and the fit errors. The fit errors were propagated into the extracted asymmetry and are roughly 0.5% of the real asymmetry for both cases. The time window we chose in this case was $\pm 1\sigma$. We found essentially the same features as we found for the spectra with no background. Of course, the Gaussian shaped background is a very strong assumption and Gaussian fit might not be the way the analysis will actually be carried out. But this shows that even without a clean cut on the elastic proton peak, we would still be able to measure the asymmetry to a few percent for a reasonable time shift (less than 5×10^{-5} ns here) by means of the background subtraction.

Conclusions

1. Assuming a -20 ppm asymmetry, both the NA and French electronics are insensitive to a helicity correlated time shift at the level of 5×10^{-5} ns over a 40-day G0 running period, with various different conditions assumed about the quality of the TOF spectra.

2. The limit of the time shift is linear in the asymmetry, given that the limit of the false asymmetry is of a fixed percentage of the actual asymmetry. So for different Q^2 in G0, we should scale this 5×10^{-5} ns accordingly. Taking the results from the "acc" simulation code written by K. McFarlane, the Q^2 ranges from 0.12 to 0.3 $(GeV/C)^2$.

(This is for detector 1 through 12. The Q^2 distribution for higher number detectors becomes more complicated and we ignore them here.) The expected elastic proton asymmetry is then within [-8.51,-2.25] ppm, assuming a 75^o scattering angle. Therefore, for the lowest Q^2, $0.12(GeV/C)^2$, the time shift limit would roughly be $6 \times 10^(- 5)$ ns.

3. The origin of the false asymmetry introduced by the time shift is the inequality between the yield that enters the time window and the yield that leaves it. In terms of the asymmetry analysis, the software should be designed to take the time integration window as centered as possible relative to the peak (although it of course must be the same for the two helicity states). A wider time window will decrease the sensitivity to a helicity correlated time shift.

4. A flat random background will not increase our sensitivity to a helicity correlated time shift.

5. The choice of a wider window may cause some contamination from the inelastic protons. We demonstrate that if we can get a good fit to the inelastic proton background, we can get a clean subtraction of these events.

One apparent source of helicity correlated time shifts might be a helicity correlated change in beam position at the target, since a change in beam position will introduce the change in the path length of the protons from the target to the detector. Thus the beam arrival time would shift via the approximate relation, $L/t = dL/dt = v$ where L is the path length, t is the total flight time of a particle, dL and dt are the shifts in path length and arrival time, and v is the velocity of the particle. The slower protons would be more sensitive to the position shift. But this induced time shift is very small. If we assume that a 10 nm shift of the beam position on the target will introduce a 10 nm change in the path length, this would cause, for the slowest protons, a helicity correlated time shift of the order 1×10^{-7} ns. Therefore, any helicity correlated time shift much on the order of something we would be sensitive to in the analysis is likely to be independent of helicity correlated beam shifts.

Another possible issue for the experiment would be the helicity independent time jitters. We would like to be sure the effect of it could be eliminated by doing the averaging on the event by event basis. Further study on this is under way.

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