K. McDonald
December 22, 1993

Features of the E-144 CCD Spectrometer, II

This note continues that of Nov. 26 with four additional comments, and a physics Appendix. Items 1 and 3 involve devices perhaps not previously foreseen.

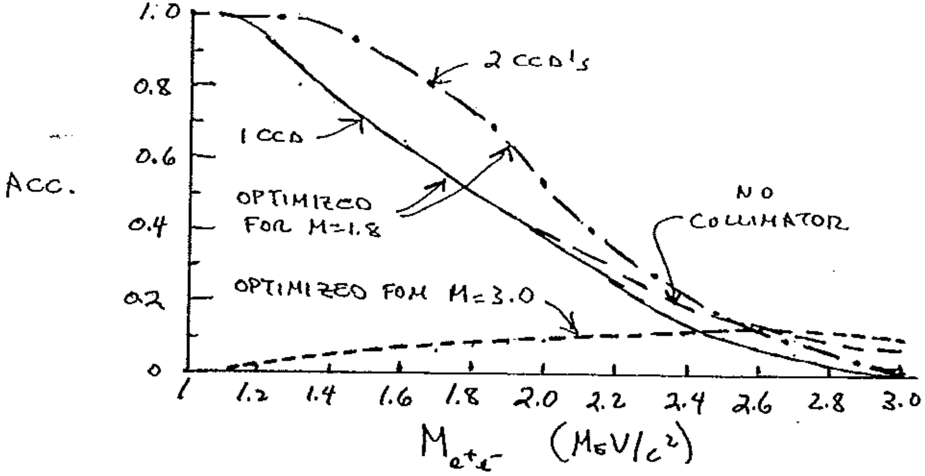
1. **Beam Stopper.**

   We would like to be able to work on the CCD spectrometer while beam is being delivered to the FFTB for other purposes. For radiation safety, this will likely require a beam stopper that can be inserted into the γ line well upstream of the CCD spectrometer building, preferably inside the FFTB tunnel near the electron beam dump.

   The stopper should be inside the beamline vacuum, since any break in the vacuum pipe results in excessive photon conversions in the associated windows.

2. **Spectrometer Acceptance.**

   The acceptance for the CCD spectrometer quoted in the note of Nov. 26 was optimized for a mass of 1.8 MeV/c^2, and is replotted in the figure below.



   For best acceptance at $M = 1.8$, the CCD's in the pair spectrometer are 7 mm from the γ-line. In this case the acceptance at, say, $M = 3.0$ is quite low (~ 0.01). The general problem is that the opening angle between the electron and positron is larger for larger mass.

   We consider three ways of raising the acceptance at higher mass:

   (a) Open the collimator. The acceptance was calculated assuming that collimators were placed in the γ-line near the electron beam dump exactly on the line from IP1 to the inner edge of the CCD's. It appears that for masses above 2.0 MeV/c^2 the collimator cuts into the acceptance slightly. However, we do not wish to omit the collimators.

(b) Optimize for higher mass. If the CCD's are placed farther from the γ-line the acceptance improves at higher mass. The figure shows the result of optimizing on a mass of 3.0, by moving the CCD's to 15 mm from the γ-line. The acceptance is now almost flat, and is nearly 10 times larger at $M = 3.0$ than when optimized for $M = 1.8$.

(c) Use larger CCD's. A relatively simple option would be to double the number of CCD's, changing the effective area of each detector arm from 17×26 mm^2 to 17×52 mm^2. Because the CCD's have no pinouts on their shorter edges this doubling configuration is straightforward; but doubling to 34×27 mm^2 is not easy.

It appears, however, that doubling the area of the CCD's only multiplies the acceptance by about 1.4, which is probably not enough to warrant the extra effort initially.

3. A New Upstream Convertor for Compton γ's.

The convertor CCD plays the dual role of converting Compton photons, and providing points on the trajectory of the resulting electron and positron to be used in the momentum measurement. With the converter CCD placed just upstream of the spectrometer magnet as proposed, there is insufficient lever arm between the conversion point and the downstream CCD's to measure the opening angle of the pair. The latter is important only if we wish to reconstruct the mass of the pair.

I now believe it would be useful to have the capability of measuring the pair mass from Compton conversions. This would demonstrate that the CCD spectrometer is working as needed for the pair creation experiment. Also, it appears that there has never been a measurement of the Bethe-Heitler pair mass spectrum, so this would provide a modest new test of standard QED.

To measure the pair mass to good accuracy, we need conditions more like those in the pair-creation experiment. Namely, the pair-creation point should be near IP2, and the multiple scattering in the convertor should be small compared to 1 MeV/c. Recall that the multiple scattering in a convertor of thickness X is $(15\ \mathrm{MeV}/c)\cdot\sqrt{X/X_0}$ where X_0 is the radiation length. Hence if we want only 0.1 MeV/c scattering, we desire less than 1/22,500 of a radiation length of material. For example, 0.6 mils of beryllium, or 0.005 mils of gold if we prefer a high-Z material.

So I propose to add a new convertor just downstream of the synchrotron-radiation monitor. This would consist of a 6″ tee (MDC part 404008) with a motion feedthrough holding the convertor foil. The motion feedthrough would the identical to that used in the synchrotron-radiation monitor.

Once the operation of the pair spectrometer is established using the convertor CCD, I would like to make a short run (< 1 day) with the thin upstream convertor to measure the Bethe-Heitler pair mass spectrum. In principle the convertor CCD would be retracted during this special run.

4. Radiation Damage to the Convertor CCD

Another issue regarding the convertor CCD is whether it will suffer rapid radiation damage. This is not known at present, but is a distinct possibility. What are the consequences if the convertor CCD dies?

If the Compton γ's convert in the convertor CCD, but we get no position information from that CCD, then the momentum measurement is compromised, and hence the energy resolution of the Compton γ suffers. Christian has begun a study of this and related issues. Here I draw a few conclusions based on hand calculations.

A typical deflection of the electron or positron track in the spectrometer magnet is 10 mm/1 m $= 10^{-2}$. To attain roughly 1% accuracy in the momentum measurement, we must know this deflection angle to $\delta\theta = 10^{-4}$, or 100 μm over a 1 m lever arm. But the γ-beam size will be about (100 m) $\cdot$ (10^{-5} rad) $=$ 1 mm at the spectrometer. So if we have no information as to the conversion point, the error on the momentum will be about 10%.

Thus if the convertor CCD dies, the precision Compton scattering experiment is seriously compromised.

However, suppose we use the new thin convertor proposed above. This would be located about 20 m downstream of IP1, and hence about 90 m upstream of the CCD spectrometer. Here the size of the γ-beam spot is dominated by the size of the electron beam, namely about 1 mm for the Compton experiment (contrasting with only a few μm for the pair-creation experiment where the laser waist at IP2 is the relevant size). This results in an angular uncertainty of only about 10 μrad at the spectrometer, so with the upstream convertor the accuracy of the momentum measurement is restored!

Of course, we lose the ability to untangle multiple conversions in a single pulse, so the event rate would have to be lowered, but the experiment could proceed. Note that the mirror of the synchrotron-radiation monitor constitutes an alternate convertor with about 20% of a radiation length, permitting use of the spectrometer even for very low rates of Compton scatters.

Appendix: Is Bethe-Heitler Pair Creation a Strong Field QED Effect?

The characteristic impact parameter in the Bethe-Heitler process is the Compton wavelength, $\lambda_C = 1/m$, so the field strength of the nucleus at this radius is $E = Zem^2 = Ze^2(M^2/e) = Z\alpha E_{\rm crit}$. In the rest frame of the pair this field is boosted to $E^\star = \gamma Z\alpha E_{\rm crit} \gg E_{\rm crit}$, since $\gamma = U_{\rm pair}/M_{\rm pair} \sim 3 \times 10^4$. So should we say that ordinary Bethe-Heitler pair creation is an example of physics at the QED critical field strength?

I think not, because the electric field isn't really critical unless it lasts for a critical time, namely the time it takes for light to travel one Compton wavelength, $t_{\rm min} = 1/m$, so that the pairs have time to materialize in the strong field. Now in the pair rest frame, the field of the nucleus appears flattened:

$$E^\star = \frac{Ze}{\gamma^2 r^{\star 2}(1-\beta^2\sin^2\theta^\star)^{3/2}} = \frac{\gamma Ze}{r^{\star 2}(\sin^2\theta^\star + \gamma^2\cos^2\theta^\star)^{3/2}}.$$

We restrict ourselves to impact parameter $r^\star \sin\theta^\star = 1/m$, and seek the length $r^\star \cos\theta^\star$ at which the field first reaches the critical field strength. This leads to the condition

$$\sin^2\theta^\star + \gamma^2\cos^2\theta^\star = \left(\frac{\gamma Z\alpha}{\sin^2\theta^\star}\right)^{2/3},$$

which is satisfied for $\theta^\star$ near 90° (the field is like a pancake), so

$$\cos\theta^\star \approx \frac{(\gamma Z\alpha)^{1/3}}{\gamma},$$

which is always less than one, and very much less than one for large γ. But since the time for which the pair is in the critical field is roughly $\cos\theta^\star/m$, this is always less than the characteristic time $1/m$. Hence we should not regard Bethe-Heitler pair creation as a strong-field QED effect.

What about the laser field? Recall that for our laser focus the Rayleigh range is about 100 wavelengths, which characterization remains true in the pair rest frame. In this frame the wavelength is $\lambda^\star = \lambda/2\gamma$. Hence the length of the critical field region is $100 \cdot 5 \times 10^{-7}/(2 \cdot 3 \times 10^4) \approx 10^{-9}$ m $\approx 2500\lambda_C$. Thus the critical field of the laser pulse lasts a long time relative to the QED time scale and we expect qualitative differences between strong-field QED pair creation and Bethe-Heitler pair creation.

It noteworthy that for high enough pair energies the laser pulse would appear shorter than the QED time scale and the some of the strong-field QED effects might be suppressed. I believe little theoretical work has been done on this possibility.