ELASTIC COMPTON SCATTERING ($\gamma + p \rightarrow \gamma + p$) at NAL

R. J. Budnitz
Lawrence Radiation Laboratory

ABSTRACT

This note examines the problems associated with a 40-75 GeV measurement of elastic Compton scattering ($\gamma + p \rightarrow \gamma + p$) and proposes a specific experimental apparatus. The paper is an elaboration of an earlier note by A. Brenner (SS-39), on the same topic. Numerical estimates are given for the important uncertainties, and methods are suggested for treating some background processes.

The Compton experiment is certainly feasible and should be one of the early measurements made in the proposed NAL tagged-photon facility.

I. INTRODUCTION

In this note I shall elaborate in detail upon the ideas of A. Brenner[1] on a method for performing elastic Compton scattering at NAL energies. I have taken over without alteration many of the same assumptions as Brenner, but have carefully studied the detailed resolution-induced errors from various sources, and the possible background problems.

II. ELECTRON BEAM

The incident tagged-photon beam has been discussed in many places, principally by Heusch[2,3] and by Diebold and Hand.[4] I will take the photon fluxes from the latter paper, noting that is is not obvious to me that these are the maximum available yields. Table I reproduces Diebold and Hand's calculated e^- and π^- yields for various beam momenta:

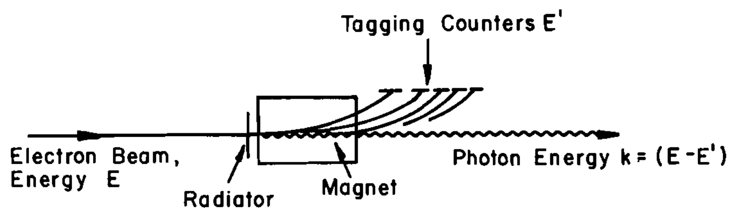
Table I.

(Assume $\Delta p/p = \pm 2\%$, solid angle = 4×10^{-6} sr, 10^{13} interacting protons)

p (GeV/c)	Electrons/pulse $\times 10^6$	π^-/pulse $\times 10^3$
40	42.0	7.0
60	27.0	7.0
80	10.0	4.0
100	3.0	1.7
120	0.6	0.4
140	0.08	0.1

III. THE TAGGED PHOTON BEAM

It is possible at NAL energies to make a slight but important modification to the "standard" tagging arrangement used in many experiments. One takes advantage of the high resolution of shower counters at energies like 50 GeV. The standard tagging scheme is shown in Fig. 1:



One knows the incident electron energy E well from the beam optics and knows the final electron energy E' from their trajectory in the magnet. The missing energy is (E - E'), which goes into the bremsstrahlung photon energy k = E - E'. The problems with radiative corrections have been dealt with well[5] and will not be discussed here.

The radiator (nominally 0.02 radiation lengths of lead) produces a bremsstrahlung spectrum of photons, all in the forward direction.

The trick is to add a shower counter behind the E' counters. With energy resolutions(fwhm) of about 1.5% at 50 GeV, one can attain superb π^- rejection, as well as improved rejection of randoms due to two E' counters firing in random. It is possible to eliminate almost all problems with π^- contamination in the beam, since even if a pion interaction in the radiator produces a forward photon, (say, from π^o decay) one will not have an "electron signature" in the tagging-system shower counter.

The π^- rejection is estimated as follows: (1) The radiator has only about 1/30 as much nuclear interaction length as radiation length; (2) the rejection of π^- in the shower counter is estimated as at least 50/1, the principal effect being shower formation by conversion of π^- to π^o in the front part of the shower counter; (3) If a π^- appears as an "electron" in the tagging system, the likelihood of its having a forward photon (for π^o decay) is at worst about 1/3, and is perhaps even 1/10 (this last is strictly my own guess). For our Compton measurement, we shall eventually require that the forward photon's energy be within a couple of percent of the missing (E - E') energy, which will help even more. Even if the last probability is unity, the basic point is unaffected.

The product of (1) × (2) × (3) is 1/30 × 1/50 × 1/3 = 1/5000. Thus even if the π^-/e^- ratio were 1/10 instead of 10^{-3} there would still be a couple of orders of magnitude left before π^- contamination would be a problem.

It is therefore appropriate to note here that if Diebold and Hand's beam could be improved in electron flux, even with substantially worse pion contamination, it would be all gain, at least for this experiment.

Diebold and Hand give a phase volume for the electron beam of $(\Delta x\, \Delta\theta_x) = \pm 0.6$ cm-mrad, and essentially the same for $(\Delta y\, \Delta\theta_y)$. We shall see that this beam emittance is an important limiting factor in the resolution attainable in the proposed Compton experiment.

IV. SPATIAL AND ANGULAR RESOLUTION

We shall assume with Brenner that the Compton cross section is given by the vector-dominance prediction. It is energy-independent and varies with t as:

$$d\sigma/dt = (\pi/EE')\, d\sigma/d\Omega = A\, e^{10t},$$

where

$$A = (1.0 \pm 0.2)\ \mu b/(GeV/c)^2 .$$

The total cross section is 0.1 μb, but we shall insist on detecting a coincident recoil proton, which limits us to recoil energies greater than about 50 MeV (range greater than 1.6 g of liquid H_2). This means $t_{min} > 0.1$, and $\int_{t_{min}}^{\infty} A e^{10t} dt = 0.35\ \mu b$. So we are dealing with a total detectable cross section of 0.035 μb, and we shall hope to detect almost all of it by detecting all recoil momenta with $t > t_{min}$.

The problem is the small-angle emission of the forward photon. Figure 2 shows the photon angle θ as a function of t for various incident momenta. Let as assume that our photon detector is 50 meters from the target. Then even with perfect spatial resolution on the position of the photon, the finite beam size and divergence give a significant effective angular uncertainty $\Delta\theta$. With $(\Delta x\, \Delta\theta_x) = \pm 0.6$ cm-mrad, consider three different ways of partitioning the emittance:

Table II.

Condition	Δx	$\Delta\theta_x$	$\Delta\theta$ at 50 meters from Δx	$\Delta\theta$ from $\Delta\theta_x$	$\Delta\theta$ in quadrature
"focussed" beam	0.5 cm	1.2 mrad	0.1 mrad	1.2 mrad	1.2 mrad
"parallel" beam	6.0	0.1	1.2	0.1	1.2
optimum in-between	1.75	0.35	0.35	0.35	0.5

Thus with the given beam emittance, angular uncertainty in θ is $\Delta\theta = \pm 0.5$ mrad. Note also that doubling the length of the lever arm 50 meters to 100 meters only gains a factor of $\sqrt{2}$ in the error in $\Delta\theta$. Figure 2 also shows how this propagates into uncertainities in the cross section, due to uncertainties in the t of each individual event:

$$\Delta\sigma/\sigma = (10\ \mathrm{GeV/c})^{-2}\ \Delta t$$

and

$$\Delta t/t = 2\ \Delta\theta/\theta \text{ from } t = E^2\ \theta^2.$$

This means that even with perfect photon spatial resolution at 50 meters, one's uncertainty about the exact kinematics of each individual event is considerable. Of course, one can obtain better cross sections by correcting the observedevent spectrum using the known (measured!) cross-section variation. The lesson is that contributions to the photon angular resolution from other sources need not be made significantly smaller than about ± 0.5 mrad, which is ± 2.5 cm at 50 meters.

We thus postulate a detection system similar to that of Brenner, but with precise dimensions and rationale governed by the above considerations (see Fig 3).

The counter C_γ is a total-absorption counter, with $\Delta E_\gamma/E_\gamma$ of about 1 to 1.5% at 50 GeV. The spark chambers S_1 and S_2 are important for several reasons. They enable one to tell the longitudinal origin of the event to precisions better than 1 cm, reducing the uncertainty in $\Delta\theta$ from that source to less than 0.2 mrad. Their crucial role, however, is to give azimuthal resolution.

Azimuthal Resolution

Consider the background $\gamma + p \rightarrow \gamma + N^*$, where N^* is any final state recoil system with mass below about 2000 MeV. (The 1% fwhm energy resolution on a 50 GeV/c photon propagates into missing mass uncertainty of about the above magnitude.) How can one differentiate such events from the elastic process, $\gamma + p \rightarrow \gamma + p$?

We can use three methods: (1) measuring recoil proton polar angle; (2) recoil energy measurements; and (3) azimuthal coplanarity.

The recoil spark chambers S_1 and S_2 will measure the proton polar angle by themselves and will achieve coplanarity measurements in conjunction with corresponding measurements on the azimuth of the photon. For that reason we insert two spark-chamber planes after 3 and 5 radiations lengths inside the photon absorption shower counter C_γ (see Fig. 3). For a 50-GeV photon, typical shower spreading errors will amount to lateral displacements with respect to the incident photon direction of about ± 2 to 3 mm. At $\theta = 5$ mrad, the displacement from the 0° line at 50 meters is 25 cm, yielding an azimuthal uncertainty for 3 mm of about ± 3 mm/25 cm = ± 12 mrad.

The proton multiple scattering (assume 4 cm of H_2 traversed) gives θ_{rms} = ±10 mrad for t = 0.1 (53-MeV proton), and ±5 mrad for t = 0.2 (106-MeV proton). Thus our azimuthal resolution is of order ±(10 to 15) mrad.

Proton Polar Angle

The measurement of the polar angle θ_p of the recoil is also limited by the same multiple scattering and is of the same order (10-15 mrad). What is of equal interest is the uncertainty $\Delta\theta_p$ propagating into θ_p by the measurement of the polar angle θ of the photon. I have estimated this as only a few (< 10) mrad.

Recoil Proton Energy

Even a crude energy measurement of the recoil proton adds further rejection against the inelastic (N^*) process. Given a photon detected with $\Delta E_\gamma / E_\gamma = \pm 0.5\%$ and $\Delta\theta$ = 0.5 mrad, one has uncertainties in predicted proton energy T_p of the order of 20% at θ of 5 mrad, and 10% at 10 mrad:

$$\Delta\theta/\theta = 2\ \Delta t/t = 2\ \Delta T_p/T_p.$$

With T_p = (53, 79, 106, 133) MeV for t = (0.1, 0.15, 0.2, 0.25) GeV/c^2, we are dealing with ΔT_p = 10 to 15 MeV. This should be of enormous help in differentiating the elastic from the N^*. One examines the individual and summed pulse heights in the counters C_{p1}, C_{p2}, and C_{p3}; for the low-t region, the third one would be in anti-coincidence.

With the limited information available at Aspen, I have not studied the N^* rejection achievable by the combination of all of the above-mentioned measurements. This will involve some computing. They are summarized as follows:

1. recoil proton polar angle θ_p known from θ of photon to $\Delta\theta_p$ = ±10 to 15 mrad; multiple scattering in θ_p of same order.

2. azimuthal (coplanarity) uncertainty $\Delta\theta$ = 10-15 mrad.

3. T_p known from θ of photon to about 10-15 MeV in region t = 0.1 to 0.25.

Thus the solid angle for the proton is limited to about 0.5×10^{-6} sr by the proton measurement.

My guess, without having done the computations, is that the total resonance cross section for N^* production estimated at about 10 times the elastic, with N^* masses less than about 2000 MeV , can be rejected by about 1000/1 or better by the combination of (1), (2), and (3) above. It had better be.

V. BEAM ENERGY AND INTENSITY DISCUSSION

Consider designing apparatus for accepting a range of recoil momenta from t_{min} to t_{max}. We have already seen that $t_{min} = 0.1$ is about right for requiring a recoil of energy > 50 MeV. The upper limit will be given by the dropping cross section. Table III gives the relevant data:

Table III.

t	Recoil energy	Fraction of cross section above t	
0.07 GeV/c^2	37 MeV	50%	Assume $A\,e^{10t}$
0.01	53	37	
0.15	79	21	
0.20	106	13	
0.25	133	8	
0.30	158	5	

So t_{max} will be about 0.25, with the possibility that a few larger t events will occur. Note that we are left with about a third of the cross section. From Fig. 2 we see that for $40 < E_\gamma < 70$ GeV, we need an angular acceptance for the photon polar angle θ of about 4 to 12 mrad. At 50 meters that is a transverse radial distance of 20 to 60 cm. We will want to fill that region azimuthally with γ detectors.

If we want to go to energies lower than 40 GeV, then the large t events would be out at larger θ's, implying a larger detector (and detector size goes like the square of θ!). Higher energies than 70 GeV would mean getting closer to the beam than 4 mrad, or else losing out on the low-t events.

We thus choose an incident electron energy before tagging of 80 GeV, and $\Delta p/p = \pm 2\%$. We tag photons from 70 down to 40 GeV. From Diebold and Hand we take an electron rate of 1×10^7/pulse, and in 0.02 radiation lengths we get 2×10^5 equivalent quanta, distributed with a bremsstrahlung spectrum. We use about half of them in our 40-70 GeV bite.

With 2 meters of liquid H_2 target and an effective cross section of 0.035 μb, we calculate a counting rate of 28/hour (same as Brenner gets). While not enormous, this rate would certainly yield a good cross-section measurement at each of several energies and t values.

It might be possible to increase the counting rate considerably even if one cannot get more intensity than in Diebold and Hand's beam. The incident electron momentum bite ($\Delta/p/ = \pm 2\%$) was chosen to keep the uncertainty in the energy of the tagged photons small.

Suppose, however, that the coplanarity constraints were sufficient by themselves to eliminate all backgrounds (one wouldn't know this, of course, until after data-taking had begun). Then one could increase the incident electron bite to, say, $\Delta p/p = \pm 10\%$, and rely on the C_γ counter's good energy resolution on the scattered photon to determine the kinematics. This would gain a factor of 5 in rate, while retaining the required kinematic constraint.

VI. REQUIREMENTS AND CONSTRAINTS ON THE NAL PHOTON BEAM FOR THIS EXPERIMENT

First and foremost, the rate must be as least as large as culculated by Diebold and Hand. As mentioned above, a substantially larger contamination of π^- in the beam could be tolerated if more electron flux was present.

Second, the electron beam's phase volume (emittance of about ± 0.6 cm-mrad in both x and y) is a limiting factor in the experimental resolution. If this could be improved (but not at the expense of intensity) it would be important.

REFERENCES

[1] A. E. Brenner, First Generation Electromagnetic Experiments at NAL, National Accelerator Laboratory 1969 Summer Study Report SS-39, Vol. IV.

[2] C. A. Heusch, Lawrence Radiation Laboratory UCRL-16830, Vol III, p. 156.

[3] C. A. Heusch, An Electron-Photon Facility for the National Accelerator Laboratory, National Accelerator Laboratory 1968 Summer Study Report B.9-68-109, Vol. II, p. 163.

[4] R. Diebold and L. Hand, Electron-Photon Beam at NAL, National Accelerator Laboratory 1969 Summer Study Report SS-49, Vol. I.

[5] See for example, T. M. Knasel, Ph. D. Thesis, Harvard, 1967, Chapter XI.

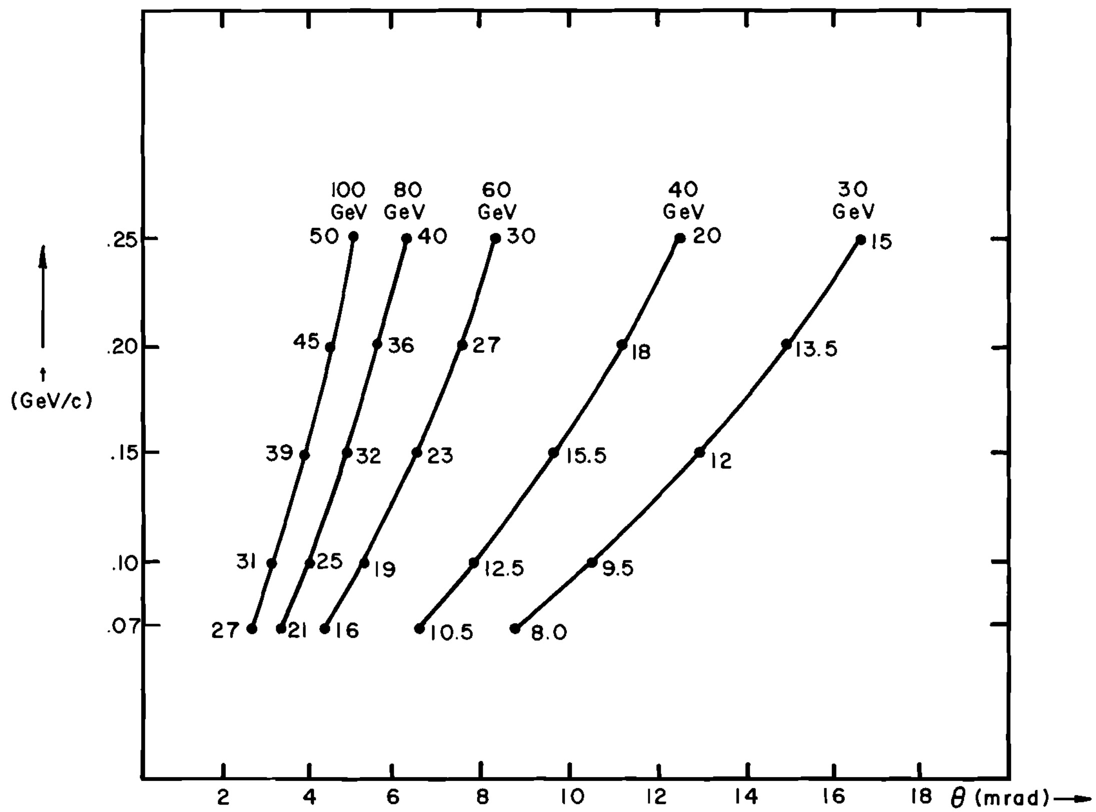


Fig. 2. t vs θ for various energies. The number at each point is the error induced by the 0.5 mrad error in θ in percent.

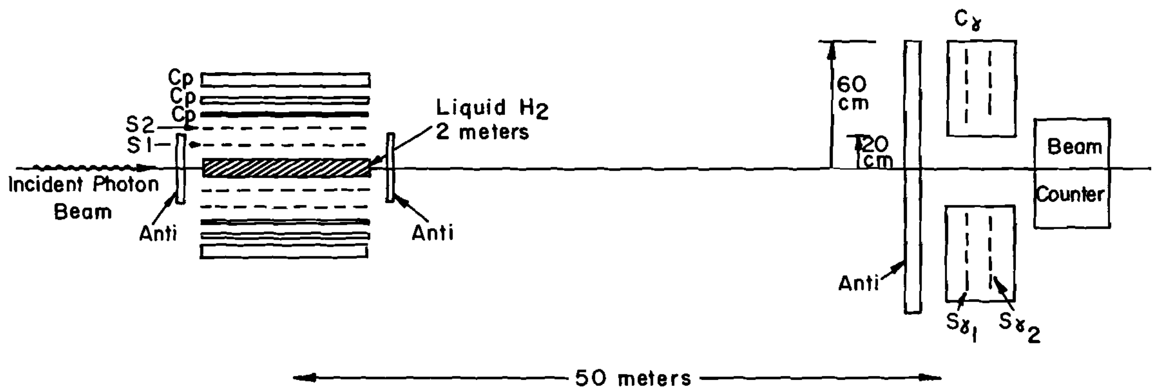


Fig. 3. Experimental layout. All counters shown are cylindrically symmetrical with respect to the beam. S_1, S_2, $S_{\gamma 2}$ and $S_{\gamma 2}$ are spark-chamber planes. C_γ and the beam counter are total absorption shower counters.