Energy Measurement of Relativistic Electrons by Compton Scattering*

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ABSTRACT

Measuring the energy of the backscattered photons from laser Compton scattering provided us the energy information of the relativistic electrons in TSL of SRRC. The photon yield, detector efficiency, detector energy calibration, and detector energy resolution would affect the final photon counting rate, and thereby influence the spectrum of the scattered photons. Method of coincidence measurement was applied and was discussed in this paper. The first couple test run results were presented here as well.

1. INTRODUCTION

Compton scattering of laser photons with relativistic electron beam can yield quasi-monochromatic photon beam. This energetic photon beam has applications in the investigation of photonuclear reaction, the calibration of the detectors, medical image, and electron beam diagnostics[1] Here we use Compton scattering to measure the electron beam energy in the storage ring of TLS (Taiwan Light Source) of SRRC (Synchrotron Radiation Research Center). The design of the optical system must take the electron beam behavior into consideration to enhance the backscattered photon yield. Optical alignment would obviously affected the photon yield, thereby the optical system should be treated carefully. The backscattered photons were produced within a very short time period since the CO_2 laser was pulsed with 30ns of pulse width. This fact indicated that the HPGe detector used in this system would detect only the background radiation from Bremsstrahlung, which was produced by the collision of the electrons and the residual gases/ions in the vacuum chamber for the most of detecting time. Unfortunately, the contribution of the Bremsstrahlung radiation in obtaining the photon spectrum was comparable to the contribution of the scattered photons. Coincidence measurement would help reducing the background to an acceptable degree.

2. THEORY

The kinematics associated with the scattering is discussed by many papers. The process is shown in figure 1. The scattered photon energy k_2 from laser photons of energy k_1 in lab. frame is[2]

$$k_2 = \frac{k_1(1-\beta\cos\theta_1)}{1-\beta\cos\theta_2 + k_1(1-\cos\chi)/E_e} \quad non-head-on \tag{1.1}$$

$$\text{or } k_2 = \frac{4\gamma 2k_1}{1+\frac{4\gamma k_1}{mc^2}+\gamma^2\theta^2} \quad head-on \tag{1.2}$$

where $\chi = \theta_2 - \theta_1$, $\beta = v/c$ with v and c the velocities of the electron and the laser light, θ is the angle between the laser and the scattered photons, and E_e is the electron energy.

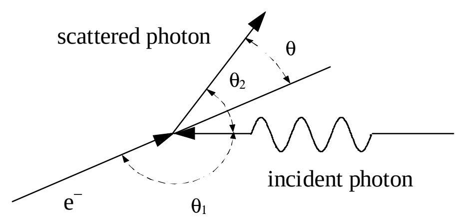

Figure 1 The schematic drawing of the process of Compton scattering

The Klein-Nishina formula shows the differential cross section *ds* for the head on collision in the electron rest frame. For the lab. frame, after the Lorentz transformation, it is rewritten as[3]

$$d\sigma = \frac{\pi r_0^2}{2}\frac{m^2}{k_1 E_e^2}\left[\frac{m^4}{4k_1^2 E_e^2}\times\left(\frac{k_2}{E_e-k_2}\right)^2 - \frac{m^2}{k_1 - E_e}\times\left(\frac{k_2}{E_e-k_2}\right)+\frac{E_e-k_2}{E_e}+\frac{E_e}{E_e-k_2}\right]dk_2 \tag{2}$$

where r_0 is the classical electron radius, and m is the electron rest mass. The photon yield Y per pulse is given by

$$Y = \frac{2N_e N_p \sigma d}{Ac\tau} \tag{3}$$

where N_e and N_p are the number of electrons and laser photons per pulse, d is the average interaction length, A is the larger one of the transverse beam size of the electron beam and the laser beam, and τ is the longer one of the pulse length of the electron beam and the laser beam. σ is the total cross section of photons and electrons.

3. SYSTEM DESIGN

The very low detection efficiency of HPGe detector at high energy (less than 0.1 relative efficiency at 10MeV) limited the choice for the laser to be employed. A lower energy (and hence the higher detection efficiency) of the backscattered photons was thereby the main criteria. The energy of the backscattered photons was 48.42MeV for a He-Ne laser and 29.49MeV for a Nd:YAG laser. A pulsed CO_2 laser with wavelength λ=10.6μm would produced the backscattered photons with maximum energy up to 3.02MeV and therefore made it suitable for this system. Figure 2 indicates the schematic drawing of the experimental setup.

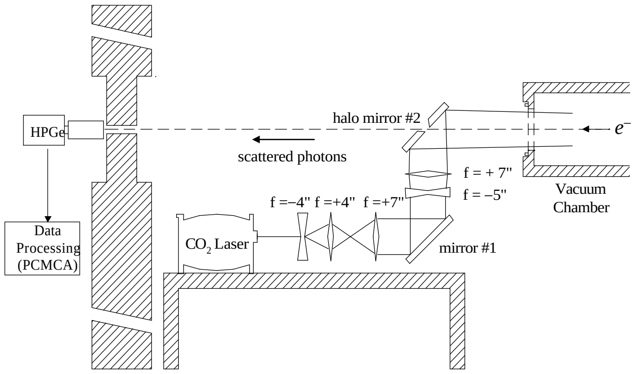

Figure 2 Experimental setup

A . Detector Energy Calibration

The traditional energy calibration using ^{60}Co and ^{137}Cs as standard sources was not convincible in this case since the energy of the scattered photons was up to 3.02MeV. The energy calibration was carried out through the gamma decay of ^{24}Na, which was the product of neutron activation of Na_2CO_3. The decay energies of ^{24}Na are 1.3684MeV, 2.7536MeV and a sum-peak of 4.122MeV. The spectrum is shown as figure 3.

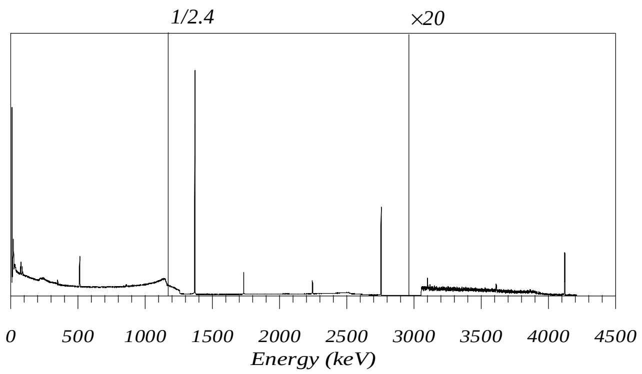

Figure 3 Spectrum of ^{24}Na

B. Optical System

The optical system design in this experiment is also shown in figure 2. The hole in mirror #2 permited the Compton backscattered photons passing through to the HPGe detector outside the shielding of the storage ring. This hole would, however, cause the loss of laser photons before their entrance into the vacuum chamber of the storage ring. The beam expander consisting of three ZnSe lenses was therefore designed to alleviate the laser loss on mirror #2. The two ZnSe lenses after the beam expander were thereby to focus the laser within the vacuum chamber, which would lessen the decrease in photon yield as a consequence of the expansion of the laser.

The beam expander could significantly lessen the laser loss; however, it also reduced the photon yield from Compton scattering. This defect was subsequently improved by the focal lenses. How were the magnifying power of the beam expander and the focal length supposed to be for a optimum photon yield? According to the previous study on this experiment[4], the magnifying power of the beam expander was supposed to be five and the focal length was designed as 4.5m for a optimum photon yield.

C. Coincidence Measurement

The using of a pulsed CO_2 laser for the sake of its higher peak power made the scattered photons be produced periodically with the same frequency of the repetition rate of the CO_2 laser. The pulse width of CO_2 laser was 30ns and therefore the photons was produced within 60ns for each laser pulse. The repetition rate of CO_2 laser was, however, at most 200Hz, i.e., 5ms of period. This information indicated that the photons were produced within a time less than 1.2×10^{-3} % of the total counting time, e.g., for 3 hours total counting time, the photons were produced only about 0.1296 seconds. What the worse was that the directional background of Bremsstrahlung was considerably high in comparison with the backscattered photons. Subsequently, the coincidence measurement became very important. Figure 4 illustrates the concept of coincidence measurement. In this figure, the laser trigger output provided a gate signal which was first shaped and delayed through a logic shaper and delay (Canberra 2055 & Ortec 427A). The signals of the detector were shaped by the linear gate and stretcher (Canberra 1454) as well after passing through the preamplifier and the amplifier. The coincidence gate opened as the gate signal arrived so as to allow the detector's signals to pass through to multichannel analyzer(MCA). Figure 5 is the relative time representation for coincidence measurement and the labels (1) to (4) correspond to the labels in figure 4. In this figure, the time length L is the time delay for gate signal (2). The width of gate signal (2) was such that it covered the drift range of the detector's signal (4).

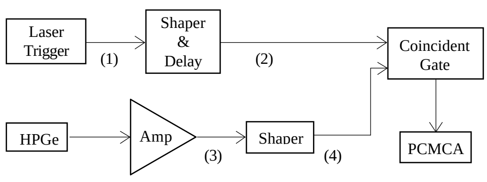

Figure 4 Coincidence measurement system schematic diagram

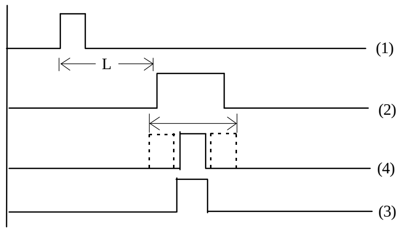

Figure 5 Time representation of coincidence measurement

4. EXPERIMENTAL RESULTS

In this experiment, the beam current of the storage ring of the SRRC was about 2mA to alleviate Bremsstrahlung radiation. Operating under multibunch mode of the storage ring, the number of electron bunches was 200 and the revolution frequency was 2.5MHz. The total counting time in acquiring the spectrum was about 3 hours. Figures 6 and 7 are the spectrum for both the background Bremsstrahlung radiation and the Compton backscattered photons. These figures illustrate the difference between the two kinds of spectrum (Bremsstrahlung and Compton scattering.) Figure 6 illustrates the spectrum obtained under the condition that the magnifying power of the beam expander of the optical system was three, the gate width was 1μs, and the collimator's diameter was 3cm; while figure 7 is for the case that the magnifying power was five, the gate width was 3μs, and the collimator's diameter was 1cm.

5. DISCUSSIONS

In the case of figure 6, the photon yield was about 9.08cps; while in the case of figure 7, the photon yield was about 10.63cps. This result corresponded to our expectation that the photon yield would be larger if the laser beam were bigger, i.e., less power loss on the halo mirror. Besides, the smaller collimator in figure 7 made the spectrum sharper in higher energy part, just as our previous conclusion under computer simulation.

The method of coincident measurement restricted only one signal passing through one gate opened. The restriction resulted from the 4μs shaping time of the amplifier. Since the gate width is less than 5μs, it was impossible for more than two signals passing through one gate. Hence our recent work is to enhance the signal counting method and to increase the photon yield.

6. ACKNOWLEDGMENTS

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7. REFERENCE

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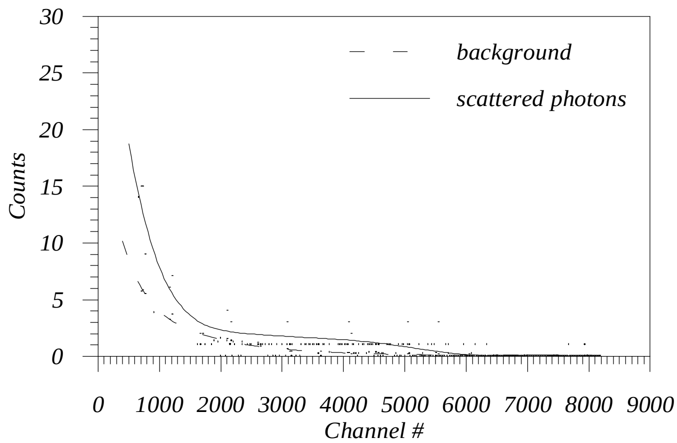

Figure 6 Spectrum with the magnifying power of the beam expander being three.

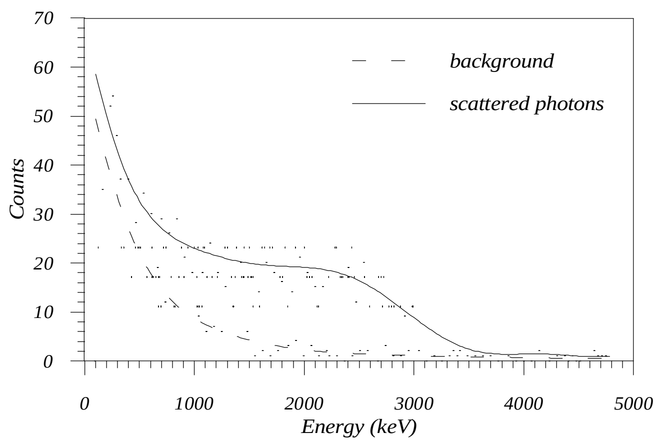

Figure 7 Spectrum with the magnifying power of the beam expander being five.