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Photon-flux determination by the Poisson-fitting technique with quenching corrections

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ABSTRACT

Single- and multi-photon spectra of pulsed γ-ray beams produced at 17, 34, and 40 MeV in the laser Compton scattering were measured with an 8" × 12" NaI(Tl) detector. By using the experimental single-photon spectra as the probability function of generating random numbers, response functions of the NaI(Tl) detector to j-fold photons ($j = 2, 3, 4 \ldots$) were constructed. The least-square fits to the experimental multi-photon spectra by the Poisson distribution consisting of the response functions were made. The multi-photon spectra measured at 17 and 34 MeV follow the Poisson distribution. A quenching phenomenon of multi-photon spectra was observed for 40 MeV γ-rays as a result of the saturation at the photomultiplier tube of the NaI(Tl) detector. The original Poisson distributions were restored from the quenched spectra using a saturation curve in the form of $y = a \cdot x^{\eta}$ with $\eta = e^{-bx}$. We discuss the accuracy of photon-flux determination.

1. Introduction

The so-called pile-up method [1] or the Poisson-fitting method [2] is routinely used to monitor the photon flux in experiments with pulsed γ-ray beams produced in laser Compton scattering. The accuracy of this method of determining photon flux depends on how precisely the pile-up or multi-photon spectrum follows the Poisson distribution. In this paper, we closely investigate the nature of multi-photon spectra measured for high-energy pulsed γ-ray beams and the accuracy of the photon-flux determination.

Quasi-monochromatic γ-ray beams are produced in the collision of laser photons on relativistic electrons. Since the large numbers of laser photons (N_{ℓ}) and electrons (N_e) participate in the collision with a small collision probability (p), pulsed γ-ray beams produced by a Q-switch laser involve multi-photons per pulse (n) that are considered to follow the Poisson distribution [1–3], $P_m(n)$,

$$P_m(n) = \frac{m^n}{n!} e^{-m}, \tag{1}$$

where m is the average number of photons per γ-pulse; namely, $m = pN$ for $N = N_{\ell} \cdot N_e$.

The total number of pulsed γ-rays can be experimentally determined from multi-photon spectra measured with a γ-ray monitor detector [1].

Experimentally, the average number of photons per γ pulse is obtained with the pile-up method [1] by

$$m^{exp} = \frac{\overline{N}_m}{\overline{N}_s}, \tag{2}$$

where $\overline{N}_m$ and $\overline{N}_s$ are the average channel numbers of the multi- and single-photon spectra, respectively.

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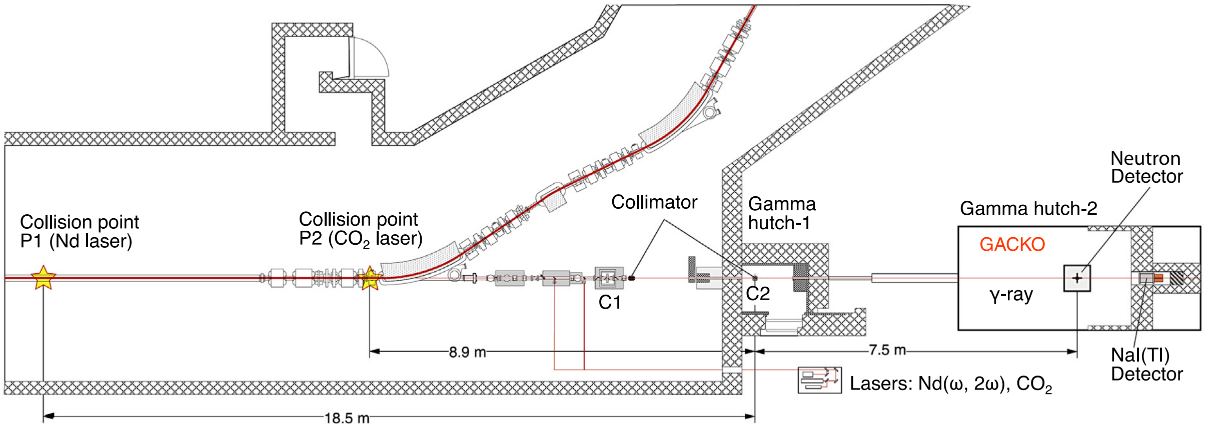

Fig. 1. (Color online) The γ-ray beam line and the experimental hutch GACKO of the NewSUBARU synchrotron radiation facility.

The total number of γ rays, N_γ^{tot} is determined by

$$N_\gamma^{tot} = m^{exp} \times N_\gamma^{pulse}, \tag{3}$$

where N_γ^{pulse} is the number of γ pulses which is equal to the total events of multi-photon spectra, $N_\gamma^{pulse} = \sum_i N_m(i)$.

2. Experiment

Fig. 1 shows the γ-ray beam line of the NewSUBARU synchrotron radiation facility. Electrons were injected at the energy of 974 MeV from a linear accelerator into the NewSUBARU storage ring. The storage ring was operated in the top-up mode at 500 MHz with 60 ps electron pulse width, where the electron beam current was kept at 300.3–299.8 mA by automated injections of electrons from the linear accelerator whenever the current dropped below 299.8 mA. The Talon laser ($\lambda = 532$ nm) [4] was operated in the Q-switch mode at 1 kHz with 40 ns laser pulse width. The laser photons underwent head-on collisions with the electrons at the collision point P1 of the storage ring, where the laser pulse at 1 kHz intersects in time with electron beam bunches at 500 MHz as depicted in Fig. 2. At the laser power 1 W (1J/s), $N_\ell = 2.7 \times 10^{15}$ per laser pulse. Since twenty electron bunches intersect with the laser pulse, $N_e = 4 \times 10^{10}$ at the electron beam current 300 mA, resulting in $N \sim 10^{26}$. Note that a typical value of m is 10 as a result of a small collision probability.

Electrons in the storage ring after the injection can be either decelerated down to 500 MeV or accelerated up to 1460 MeV. Pulsed beams of 17 and 40 MeV γ-rays were produced at electron beam energies, 684 and 1061 MeV respectively, in an operation of the storage ring in the decay mode, where the electron beam current decreased with time. The electron beam energy referred to is the nominal energy which is calibrated with the accuracy of the order of 10^{-5} [5].

Pulsed laser-Compton scattering γ-ray beams have long been used in photoneutron cross section measurements at the experimental hutch GACKO (Gamma Collaboration Hutch of Konan University) of the NewSUBARU facility. During the photoneutron measurement, multi-photon spectra were measured with a large-volume (8” × 12”) NaI(Tl) detector which has 100% detection efficiency. Single-photon beams were produced in a CW operation of the Talon laser with a reduced laser power. Single-photon spectra were also measured with the NaI(Tl) detector before and after the photoneutron measurement.

3. Single-photon spectra

3.1. Generating single-photon spectra by random numbers

Fig. 3 shows an experimental single-photon spectrum, the number of counts $N_s(i)$ versus channel number i ($i = 0, 1, 2, 3, \ldots$) measured at 34 MeV. We generated random numbers with the experimental spectrum as the probability function as follows. We define a finite numerical range of $N_s(i)/\sum_i N_s(i) \sim N_s(i+1)/\sum_i N_s(i)$ and devote the range to channel i. We generated uniform random numbers between 0 and 1 and incremented the number of events at channel i when the random number falls in the range $N_s(i)/\sum_i N_s(i) \sim N_s(i+1)/\sum_i N_s(i)$. A spectrum of 20,000 random numbers thus generated is shown by the solid line in Fig. 3 after normalized to the experimental spectrum. Thus, we generated random numbers with the probability function identical to the experimental single-photon spectrum.

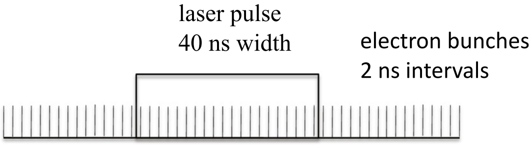

Fig. 2. Collisions between laser photons and relativistic electrons.

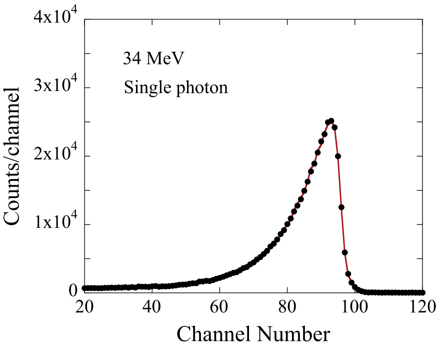

Fig. 3. (Color online) Single-photon spectrum at 34 MeV. The solid line shows a spectrum of 200,000 random numbers generated with the experimental single photon spectrum as the probability function. The spectrum of random numbers are normalized to the experimental spectrum.

3.2. Response functions to multi-photons

The NaI(Tl) detector with the time response on the order of µs cannot resolve in time scintillation lights produced by multi-photons when they are incident on the detector during the γ-pulse width (40 ns). We can construct response functions of the NaI(Tl) detector to high-energy multi-photons by generating random numbers in j-fold. Fig. 4 shows the response functions to j-fold photons ($j = 1, 2, 3, \ldots, 20$) at 34 MeV.