Nuclear Physics with MeV photons at SPring8

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The 8 GeV storage ring at SPring-8 [1, 2] is used mainly as a synchrotron radiation light source. However, it can be also used for nuclear physics purposes as a source of γ rays. The low-energy photon production from the Compton backscattering (CBS) has two advantages. The energy spectrum of the γ rays consists of much more high energy photons than for the Bremsstrahlung method. Additionally, the resulting photons are naturally polarized, up to 100%, depending on the scattering angle in the c.m. system of photon and electron.

Since the energy-loss of 8 GeV electrons for one circulation is about 30 MeV, there is no loss of electron number in the storage ring if electrons lose thier energy less tahn 30 MeV. Thus, experiments can be performed parasitically, independent of other experiments. Also, the power needed to accelerate the struck electron to the mean beam energy is negligible (e.g., to accelerate 10^{10} electrons per second by 10 MeV one needs 0.16 W). The radio frequency (RF) cavities for acceleration are working at a frequency of 508.58 MHz, thus the beam is nearly continuous with a bunch separation time of $\sim$2 ns.

If the laser light were backscattered to the electron beam direction, the photon maximum energy becomes

$$\omega_{max} = \frac{4\omega_0 E_e^2}{m^2 + 4\omega_0 E_e}. \tag{1}$$

Table 1 lists the available energy of the Compton backscattered photons. To produce γ rays with a few MeV for nuclear resonance fluorescence (NRF) experiments, lasers with wavelengths of the order of a few 100 μm are needed. Such a laser system for the light with 100$\sim$200 μm is available [3]. Thus we can get a high intensity MeV γ rays from the 8 GeV electron beam. For example, the photon energy of the 120 μm laser light is 0.0103 eV, and those of the 240 μm laser light is 0.00517 eV. When we irradiate these laser lights to the 8 GeV electron beam, we can get the maximum γ energy of 10.11 MeV and 5.07 MeV. The Compton backscattered photons is focused within $\Gamma \approx m/E_e = 0.063$ mrad. This means that the emission angle of photons are almost determined by the divergence angle of the 8 GeV electron beam at the collision point.

Since the photon energy of the laser light is extremely low, the laser beam contains a huge number of the quantum photons compared with the case of the ultra violet laser (more than a factor of 100 !). Since the energy loss of the recoiled 8 GeV electron is very small, the recoiled electron can again circulate in the storage ring. This means that we can irradiate the 8 GeV beam with a higher intensity laser light. There is a possibility for us to easily obtain the γ intensity of more than 10^9/sec. If we install the laser system at the inside of the storage ring and make the laser cavity at the laser-electron collision point, the collision with the laser light will be increased by a factor of 10^6 because that the laser cavity stores a huge number of photons.

Table 1: Energy of Compton backscattered photons from 8 GeV electrons. It is worthy noting that the infra-red laser beam contains much more photons if we use the same power laser. The notations λ, ω_0, ω and Γ stand for the laser wavelength, the laser photon energy, the maximum energy of the Compton backscattered photon, and the half width of the scattered angle, respectively. The last column shows the photon intensity included in the 1 Watt laser.

λ	ω_0	ω	Γ (mrad.)	I(photons/sec)/Watt
200 nm	6.20 eV	3450 MeV	0.085	1×10^{18}
350 nm	3.54 eV	2421 MeV	0.076	1.76×10^{18}
500 nm	2.48 eV	1860 MeV	0.073	2.52×10^{18}
...	...	...	...	...
120 μm	0.0103 eV	10.11 MeV	0.068	6.06×10^{20}
240 μm	0.00517 eV	5.07 MeV	0.066	1.21×10^{21}

Fig. 1 shows the excitation and decay processes of a nucleus. The nucleus is first excited by a photon. The excited level decays by γ emission into the low-lying levels. In the past, using this process called "nuclear resonance fluorescence", many important experiments were carried out to study the levels excited via the magnetic and electric transitions [4, 5]. Recently, the NRF method are used to investigate the nuclear scissors mode [6, 7], which is one of the important collective motions of nuclei. Thus, the promising extension of the NRF experiment at SPring-8 is noteworthy.

Let's consider the γ ray detection ratio from the NFR experiment at SPring-8. We examine the case of the M1 excitation. The full width of the decay process is the sum of all possible decay widths. The width and the excitation strength are related by

$$\Gamma_i = 8\pi \sum \frac{L+1}{L((2L+1)!!)^2} \left(\frac{E_0 - E_i}{\hbar c}\right)^{2L+1} \cdot \left(\frac{2J_0+1}{2J_i+1}\right) \cdot B(\pi L)\uparrow. \tag{2}$$

The absorption cross section is related to the width Γ_0 as,

$$I_{abs} = \pi^2 \cdot \left(\frac{2J+1}{2J_0+1}\right) \cdot \left(\frac{\hbar c}{E_x}\right)^2 \cdot \Gamma_0. \tag{3}$$

In the case of the $M1$ excitation from the 0^+ state to the 1^+ state, the width can be written in a more simple way using the transition matrix B(M1) as

$$\Gamma_0(0^+ \rightarrow 1^+) = 8\pi \cdot \frac{2}{9} \cdot \left(\frac{E_x}{\hbar c}\right)^3 \cdot \frac{1}{3} \cdot B(M1)\uparrow, \tag{4}$$

$$\frac{\Gamma_0}{(0^+ \rightarrow 1^+) meV} = 3.8 \cdot \left(\frac{E_x}{MeV}\right)^3 \cdot \frac{B(M1)\uparrow}{\mu_N^2}. \tag{5}$$

Since the nuclear magneton μ_N^2 has a relation of $\mu_N^2 = 0.011 e^2 \cdot fm^2$, we get the following equation,

$$\frac{I_{abs}(0^+ \rightarrow 1^+)}{MeV \cdot fm^2} = 1.2 \cdot 10^{-3} \cdot \left(\frac{MeV}{E_x}\right)^2 \cdot \frac{\Gamma_0(0^+ \rightarrow 1^+)}{meV} \tag{6}$$

For an $M1$ excitation with an excitation energy of about 3 MeV, an strength of about 1 μ_N^2, and the decay width Γ_0 of 0.1 meV, one gets I_{abs} of about 0.013 MeV·fm^2. Assuming

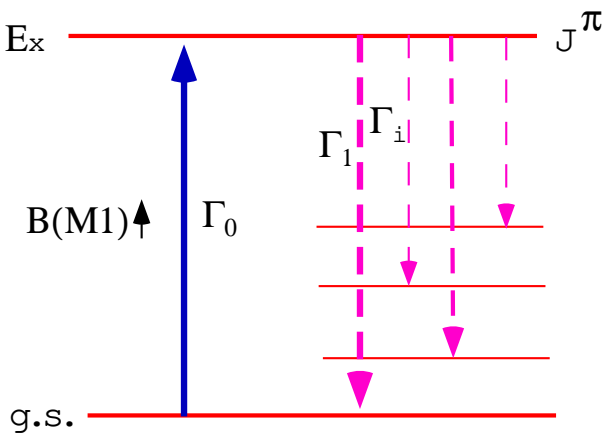

Figure 1: Excitation and decay diagram of excited levels in a nucleus.

a target density of $10^{22}/\mathrm{cm}^2$ (e.g., 200 mg of ^{12}C) and a photon flux of $10^8/(5\ \mathrm{MeV})/\mathrm{second}$, one gets a counting for that certain excitation of about 26 Hz into the full solid angle of 4π. If we use a γ ray detector with an efficiency of 2%, we can accumulate the total counts of about 45,000 for one level.

Recently, a new possibility is suggested by Litvinenko *et al.,* [8]; a monochromatic γ beam of $\sim$12 MeV has been produced via Compton backscattering between the 500 MeV electrons and free-electron laser photons. They claim that the intensity of 100% linearly polarized γ rays will amount to 10^9-10^{10} per sec.

On the base of these considerations, we are constructing a new facility for generating MeV gamma rays at SPring-8.

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