Photon Nuclear Science with backward Compton gamma rays

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Abstract

Recent developments of the synchrotron radiation facilities and intense lasers are now guiding us to a new research frontier with probes of a high energy GeV photon beam and an intense and short pulse MeV γ-ray beam. We discuss new directions of the science developments with photo-nuclear reactions with the inverse Compton γ-rays for studying hadron structure, nuclear structure, astrophysics, materials science, as well as for nuclear technologies.

1 Introduction

In the scientific field called "photon nuclear science", many applications from basic science research to the biotechnology are performed with photon beams. Nuclear excitation, synchrotron radiation, bremsstrahlung, and inverse Compton scattering are used to obtain these photon beams. Starting from the observation of X rays by Röntogen in 1985, the applications now reaches at the sophisticated technology developments with help of the fast computer such as PET (positron electron tomography) and the observation of chemical dynamics. These fields will be more widely extended for contributing to nuclear science and human life.

Historically, the scientific developments have mostly been made by observing the emitted-, reflected-, and absorbed-lights from the objects. Observations were made by naked eyes for a long time in human history. The novel invention of microscopes in 1590 and telescopes in 1608 with optical-lens combination changed the means of observation very much, and triggered to investigate the microscopic world as well as the macroscopic world, the universe. After 400 years later, we have acquired the deep knowledge both on the microscopic and macroscopic worlds: The basic elements of the microscopic world consist of quarks, leptons, and their mediators (photon, gluons, bosons). The universe starts from a big bang, and creates nuclear elements through various reaction processes in stars in the circular transmigration. Many of these observations have been made by using the probe "photon".

In case of the studies of the microscopic world, interesting developments are now going on. For example, hadron physics are studied with GeV photon beam obtained via the inverse Compton scattering of laser photons by 8 GeV electrons at SPring-8 [1, 2, 3]. Recent experiments report that a new hadron consisting of 5 quarks (two u-quarks, two d-quarks and one anti s-quarks (called Penta-quark particle) may exist at 1540 MeV [4]. This report has triggered world-wide enthusiasm of further experimental and theoretical researches since there is no explicit reason of quark theory to prohibit the existence of hadron particles with four, five, six quarks and so on. Although the existence of the penta-quark particle are now in controversial situation since the new high statistics experiments at the Jefferson laboratory presented the negative results on the penta-quark particle at 1540 MeV [5, 6], the hunting of "pentaquark particles" continues in future until we understand the basic reason to govern the quark world.

Apart from the hadron physics with GeV photons, our scientific development with photons seems to arrive at the birth of a new era. The laser beam is extraordinary intensified with the usage of new optical crystals [7], making the laser acceleration possible. The operation of a high intensity free-electron laser (FEL) becomes feasible [8, 9], and it is possible to use a high power infrared laser with a kW level for further applications in combination with electron beam. Surprising discovery has been achieved in obtaining electron beam with laser acceleration in 2004 [10, 11, 12, 13]. Considering these recent developments of laser technologies, a new feasibility is now extended for a unique feasibility that is to utilize the inverse Compton process for obtaining a high intensity photon beam in the MeV energy region. Since the inverse Compton photons are naturally polarized, we can employ MeV γ-rays for new experiments with polarization observables. These samples are follows:

1. High precision measurements of nuclear resonance fluorescence and Mössbauer effects are much feasible for studying the nuclear structure, the basic symmetries like the parity non-conservation, materials science, bioscience, and archeology.

2. Application of nuclear physics for astrophysics: Simulation experiments by producing high-flux g-rays are feasible. We can approach to answer the questions concerning the nuclear synthesis in supernova sites.

3. Application for nuclear engineering: A very small amounts of nuclear contaminant would be possible to be detected if a high resolution and intensive photon beam is available [14].

4. Observation of basic quantum effects would be realized by using a high-intensity polarized photon beam.

In the present report, We wish to review the history of photo nuclear science and to discuss new developments in physics with the inverse Compton γ-ray beams. In Japan, China, Taiwan and Korea, excellent synchrotron radiation facilities are in operation or under construction. It would be a nice timing to discuss the possibilities performed with inverse Compton photon beam.

2 What is the future of inverse Compton photon beam?

Recent technologies to deliver a high intensity photon beam are enormously enhanced with an appearance of the 3rd generation synchrotron radiation facilities. Intrinsic feature of photon is the fact that photon is boson, which can be coherently overlapped in space and in time. For this reason, photon energy density increases without limitation whenever the coherence condition is satisfied. A good sample is the laser acceleration of monochromatic electron beam at E_e= 20-200 MeV with a resolution of about 5% [10, 11, 12, 13]. One can say that the dream predicted by Tajima and Dawson [15] in 1979 really comes true. The important aspect here is the fact that we can really control a high intensity photon in space and time. This feature is also used for the inverse Compton scattering process. Figure 1 shows a schematic illustration of the inverse Compton scattering. When the laser light is backscattered to the electron beam direction, the maximum photon energy

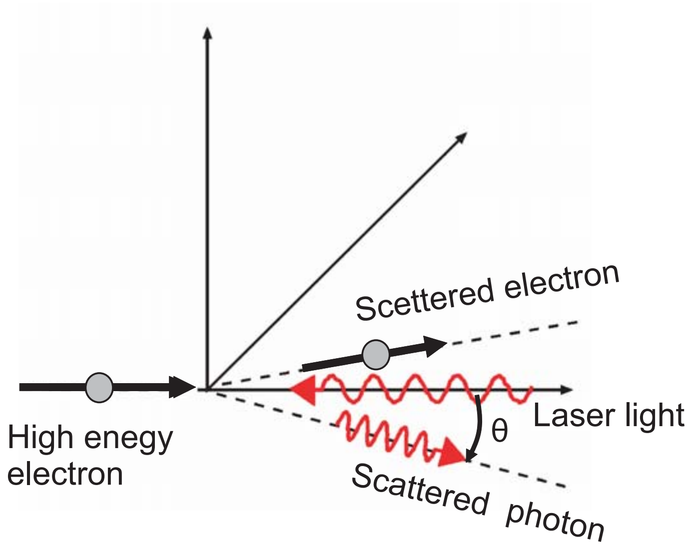

Figure 1: Scheme of inverse Compton process via the collision between high energy electron and laser light. When a laser light collides with a high energy electron, the photon is recoiled and is boosted up its energy by a factor of about $4\times\gamma^2$ thanks to the relativistic effect, where $\gamma = E_e/m_e c^2$ is the Lorentz-FitzGerald contraction factor.

becomes

$$E_\gamma^{max} = \frac{4\nu E_e^2}{(m_e c^2)^2 + 4\nu E_e}, \tag{1}$$

where ν is the energy of incidence laser, E_e is the energy of the electron beam, m_e is the electron mass. The features of the inverse Compton scattering are

1. high energies,

2. high linear and circular polarizations,

3. short pulse width, and

4. high emittance.

All these features stem from the properties of the electron beam. It is noted that when the energy of incidence laser photons is relatively high compared with the electron beam energy, almost mono-energy beam is available [16, 17, 18, 19, 20]. Thus, using this relativistic kinematic, it is possible for us to obtain the quasi-monochromatic photon beam at high energies.

An important question to be addressed is "how can we generate a high intensity photon beam?". In fact, the intensity of photon beam is weak in the past. This is a serious disadvantage in case of the nuclear physics experiment, which requires a high-intensity photon beam to deduce small nuclear cross-sections. The hadron beam intensity is now exceed to 10^{15} /second and widely used for the studies of nuclear science whereas the photon beam intensity in the MeV - GeV energy region remains at a level of 10^6 /second. This unfavorable situation for photon beams is now at the turning point thanks to the recent novel developments of

1. short-pulse and high-intensity electron gun,

2. acceleration of electron beam,
3. control system with high-speed personal computers, and
4. short-pulse and high-intensity laser.

At present, the modern storage ring can store the electron beam at the GeV energies with an intensity more than 100 mA (6×10^{17} electron/second). The laser intensity amounts to the 10 kW range. If this laser is a far-infrared laser with a wave length of 100 μm, the laser energy is about 0.01 eV. The photon intensity is 6×10^{20} /second. Assuming the laser and electron beams can be focused with the same size of the order 1 mm^2 and the inverse Compton process is used for obtaining a MeV photon, the intensity of such photons is estimated to amount to 10^{18} /second. This intensity is extremely higher than the present level of the photon intensity. Many scientists imagine a dream that the photon beam with an intensity of 5×10^{13} becomes feasible in the near future [21]. For example, Ruth et al., [22, 23] at the Stanford accelerator facility now test a new machine to obtain a photon beam in the X-ray energy region from the inverse Compton scattering. Ruth's statement is somewhat shocking. The essential point of his statement is the fact that big machines like a 3rd generation synchrotron radiation (SR) facility may not be necessary for developing the science with X-rays in future, and it would be possible to obtain a compact alternative machine delivering an intensive X-ray beam compatible with those from the expensive SR machine.

Remarkable developments of the free electron laser (FEL) are a remarkable mile stone in recent years. A high power FIR laser of 10 kW class is competitively developed [9, 24]. As an promising extension of this rapid scientific developments, the construction of the energy recovery linear-accelerator (ERL) facility is discussed [25]. If the dream comes true, the photon intensity from the inverse Compton scattering will reach at 10^{13} /second, and new kinds of nuclear photo-science will be promised. At TUNL (Triangle University Nuclear Laboratory), a high intensity photon beam has been achieved using the inverse Compton scattering process between the stored electron beam and the FEL light [26]. Some fruitful experiments aiming at the studies of nuclear physics and nuclear astrophysics are pursued with a photon intensity of 10^7 /second. If the photon intensity of the order 10^{13} /second will be realized, the world of these studies will be completely changed.

First, let's consider a different challenge of obtaining a high energy photon beam using the coherency in the collision process between electron and photon. Figure 2 illustrates what happens for the synchrotron radiation if the electrons move coherently in a dipole magnet. When a single electron is bent in the dipole magnet, the basic QED process is described in terms of the coupling constant with the bare electron charge e, resulting the radiation is proportional to $e\times e$. In this case, the intensity of synchrotron radiation is, of course, proportional to the number of electrons in the beam bunch passing through the dipole magnet. When the bunch of the electron beam is short enough to move together in the size of the wave length of radiated photons, a strong photon radiation is expected to be emitted thanks to the coherent effect. In fact, such enhanced radiations have been experimentally observed at the linear accelerator facility of Tohoku University [27].

Second, we consider the case of the inverse Compton scattering. Figure 3 shows three types of the Compton scattering processes. It is well known that the cross section of the Compton scattering process from the nucleus with an atomic number Z is proportional to Z^2. Since the individual protons in a nucleus are trapped in the nuclear potential governed by the strong force and the size of the nucleus is very small as the order of 10^{-13} cm, photon colliding with the nucleus interacts with protons coherently. The process with

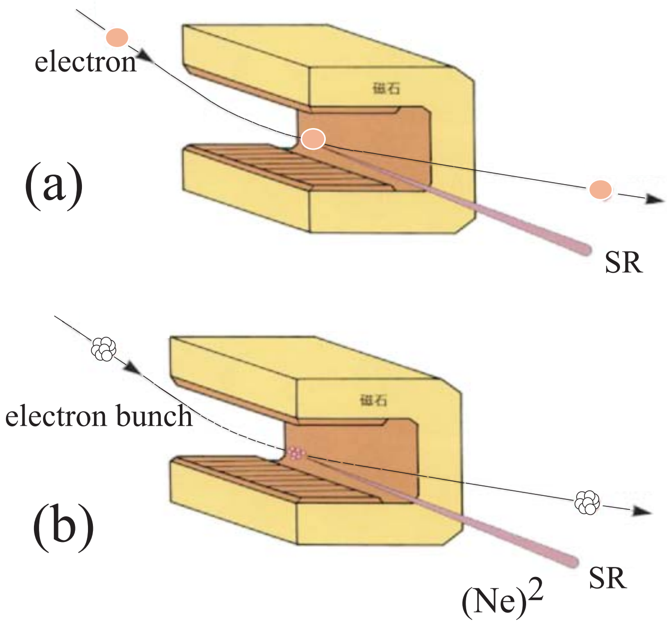

Figure 2: Synchrotron radiation with a single electron and an electron bunch with a number of N. If the N electrons in the bunch are bent in coherent in a dipole magnet, the synchrotron radiation from the electron bunch is enhanced by a factor of N^2 compared with that from a single electron.

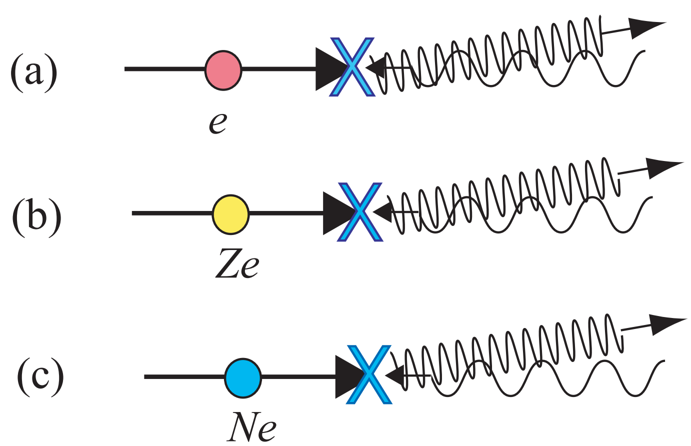

Figure 3: Compton scattering processes of photons from (a) single electron, (b) atomic nucleus with a charge Z, and (c) a beam bunch with N electrons. The scattering cross sections are given by $\sigma_T^e = \frac{8\pi}{3}(\frac{e\times e}{4\pi\epsilon mc^2})^2 = 6.7\times10^{25}$ cm^2, $\sigma_T^Z = Z^2\sigma_T^e$, and $\sigma_T^N = N^2\sigma_T^e$, respectively.

the electron bunch is more complex. Usually, the size of the electron beam bunch is not small, and the individual electrons in the beam bunch are not trapped in the potential, and moved randomly in the space of the beam size as a molecule of an ideal gas. If the electrons are trapped in the beam bunch and the size becomes small as the order of the wave length of incoming photons, the cross-section could be enhanced with the order proportional to $N^2 \times \sigma_T^e$, where σ_T^e, is the Thomson cross-section for the photon-electron scattering. This situation is illustrated in Fig. 3(b). In fact, the mirror or polished mirror-like metal surfaces used in our common life reflect light with a 100% reflectivity. This is due to that many electrons in metal move coherently against a photon, and as a result the photon is completely reflected.

Now let' consider the collision between photons and the shortly bunched electron-beam under the special condition illustrated in Fig. 4. What we wish is to trap the electrons in the beam bunch with a special potential. The key ingredient is the method for generating the electromagnetic field to confine electrons even for a short instance. On the basis of the idea given by Hartemann et al. [28], this trapping mechanism is given by irradiating the electron beam with a short-pulse and high-intensity laser along the same direction of the electron beam direction. Since the laser provides a very strong electromagnetic field, the electrons in the beam bunch is trapped for a short period. This kind of trapping mechanism of electrons is now a well known concept when we consider the FEL machine: the SASE (Self-Amplified Stimulated Emission) mechanism is the most important ingredient.

When the electron beam bunch is irradiated with a high intensity laser, some parts of the electron group in the beam would be confined in the laser potential for a short period. In the same instance, we shoot the electron beam from the forward direction with another laser light split from the same laser. For example, if 1000 electrons associate with the coherent scattering, the cross-section of the inverse Compton scattering is enlarged by a factor of 10^6. This means that the reflectivity of the laser becomes large, and the laser energy is boost up by a $4 \times \gamma^2$ factor as well. The possibility of obtaining the coherent scattering with many electrons is not small: The electron beam bunch with an intensity of μA with MHz repetition contains about 10^6 electrons. If 1000 among 10^6 electrons is confined in the laser potential in the short period of the laser irradiation, the coherent Compton scattering is expected to happen. Such trails with the N^2 effect in coherent inverse Compton scattering are made to generate a high flux X-rays and for the application of cancer therapy [17, 18, 19, 20].

At Kansai Photon Science Institute (KPSI), there is a betatron accelerator. The beam bunch from this betatron accelerator is rather short. A high intensity laser is also guided into the same experimental room. Thus, the KPSI is the best place to check the feasibility of the coherent inverse Compton scattering with the N2 effect. Another possibility of testing the N^2 effect is to use the electron beam from the laser acceleration. Recently, the laser acceleration of electron beam has been realized [7, 10, 11, 12, 13]. The beam bunch of this laser driven electron beam should be extremely small with a size much less than the laser wave length of about 0.1 μm. It is interesting to consider what happens when the laser collide with this electron beam from the laser driven acceleration (see Fig. 5). We can expect the same coherent inverse Compton scattering from the electron beam since the electron beam bunch is expected to be very short because of the laser acceleration mechanism.

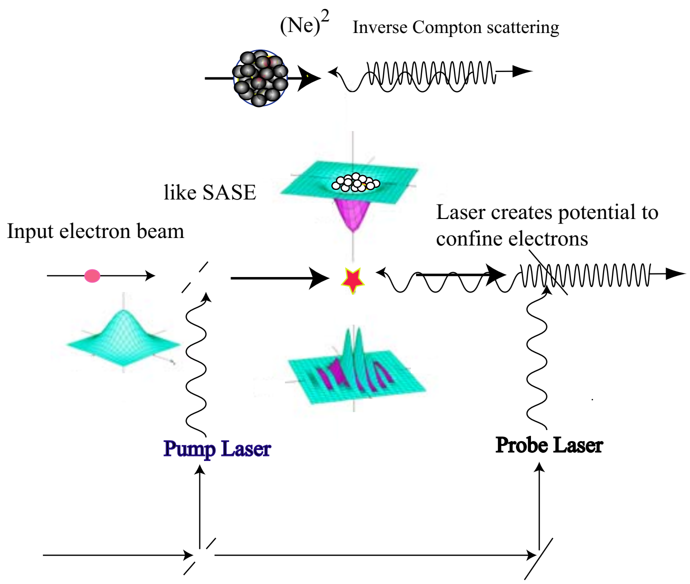

Figure 4: Scheme illustration of the coherent backscattered Compton process via the collision between high energy electron and laser light. When a laser light collides with a high energy electron, the photon is recoiled and is boosted up its energy by a factor of about $4\times\gamma^2$ thanks to the relativistic effect, where $\gamma = E_e/mc^2$ is the Lorentz-FitzGerald contraction factor. When a bunch of the electrons are trapped in a strong laser potential, the electrons in the potential move coherently, and scatter photon with a large cross-section. In such case, the reflection rate is enhanced by a factor of $(Ne)^2$, where N is the number of electrons associated with the collision process.

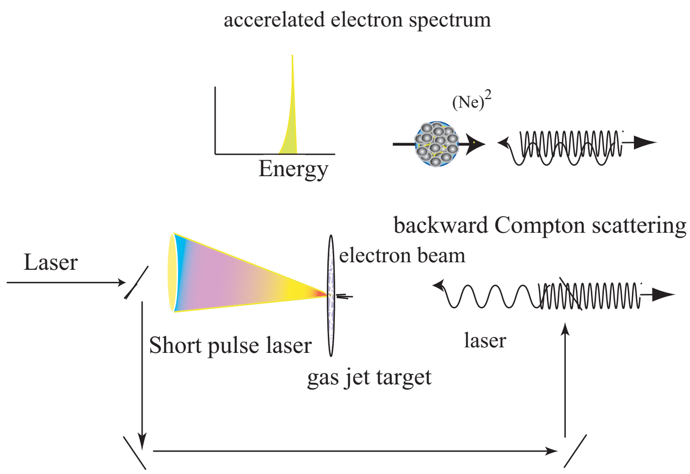

Figure 5: Scheme illustration of the coherent backscattered Compton process via the collision between high energy electrons from laser driven acceleration and laser light.

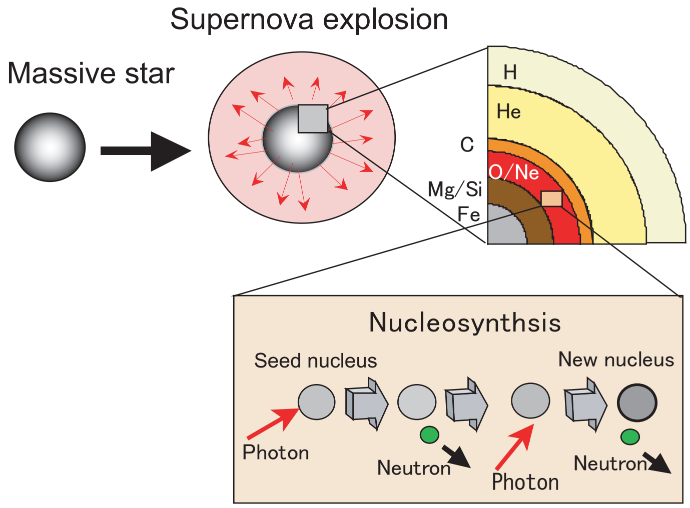

Figure 6: Schematic drawing to explain the production mechanism of p-nuclei in the strong photon field at supernova explosions. At the death of a star with a mass by about twenty times heavier than the mass of the sun dies, the core irons in the heavy star start to capture electrons and explode. As a result, nuclei at the core of star become neutron rich, leading to a neutron star. However, nuclei at the outside of the supernova star capture neutrons, and become heavier. This heavy nuclei are irradiated with extraordinary strong photons from the supernova explosion at the star center. There is a possibility to make neutron deficient nuclei after repeating two (γ,n) processes. This kind of nuclei is called "p-nuclei". (by courtesy of T. Hayakawa).

3 Nuclear Photon Science with high intensity γ-rays

A famous study of the nuclear structure using a photon beam has been made by Bothe and Gentner in 1937 [29]. They obtained the cross-section for the ^{63}Cu(γ,n) reaction from the radioactivity induced by γ-radiation from the Li(p,γ) reaction. The cross-section value is about 5×10^{-26} cm^2, which corresponds to those of exciting the giant dipole resonances (GDR) in nuclei. Actually, the existence of such GDR excitation mode has been commonly recognized from the work by Baldwin and Klaiber [30] in 1947. Since then, many discoveries were reported on the nuclear level excitations. The "nuclear giant resonances" have been one of the important subjects in nuclear physics for long time. "Photon" played an important role to probe the nuclear structure because the nature of photon is completely well understood in terms of QED. It should be noted that the observation of γ-ray de-excitation is also a powerful tool to study nuclear level structures.

Needless to say, the discovery of nuclear resonance fluorescence (NRF) is a benchmark event in the development of nuclear physics. Especially the finding of the recoil-less NRF by Mössbauer brought a great benefit for the materials science. Combining NRF methods with a high-resolution Ge detector, nuclear structure has been studied for many stable nuclei [31, 32, 33].

In recent years, demand to study the nuclear synthesis processes with photons increases since some new observations in cosmos are reported. Especially, the nuclear synthesis at the site of supernova explosion is considered to be of importance in understanding the story to create nuclear elements from light to heavy. In order to experimentally simulate the nuclear reaction processes in the photon fields at the supernova site, a extremely high-intensity photon-beam is required.

Figure 6 shows a scheme to illustrate the creation process of p-nuclei at the supernova site. The mechanism of the p-nucleus synthesis was one of the mysteries in astrophysics. Hayakawa et al., [34] conclude on the basis of the systematic nuclear-abundance ratio and of the theoretical network calculation that the p-nuclei are created by sequential two (γ,n) processes in ultra-high γ-ray fields at the supernova site. It becomes gradually clear that in our solar system, the elements up to heavy uranium are synthesized by repeating supernova explosions several times and the $s-$ and $r-$processes in stars of the Galaxy. Further detailed studies of the nuclear synthesis in cosmos are needed for understanding the birth history of the solar system, and the earth. Especially, the explosion mechanism of supernovae remains as an unsolved problem. Knowledge of detailed nuclear structures of the fp-shell nuclei is still required. The NRF experiments with high-intensity photon beams at E $\geq$ 5 MeV are useful to understand the level structures concerning the $E1$ and $M1$ excitations. The information on the $M1$ strengths in nuclei is especially important for the neutrino absorption calculations for construction of a large-scale detector to detect the supernova neutrinos, which are expected to appear within a few seconds when a supernova explosion happens. Thanks to the recent developments of nuclear theories, more sophisticated experiments are also required to refine the theoretical calculations. On basis of the new developments of shell-model and alpha-cluster calculations, new experiments for photo-absorption processes are urgent for further improvements of theories.

If a high-intensity photon beam via the inverse Compton scattering process, a great benefit in physics experiments is "linear and circular polarization". Circular polarized photon beam is useful for the parity non-conservation (PNC) experiment to study the weak-boson and nucleon coupling in nuclear medium. The origin of the mirror symmetery violation in β-decay is now well understood as a manifestation of the exchange process of charged weak bosons, W^+ and W^- after the PNC discovery by Wu [35], following the suggestion by Lee and Yang [36]. Observations of the PNC effect in nuclear excitation are not quite new. The trial to observe the PNC effect was first reported by Tanner in 1957 [37], followed by the famous work of Feynman and Gell-Mann [38] for the universal current-current theory of weak interaction. In the PNC effect in nuclear excitations, neutral weak boson Z^0 is responsible, and strongly coupled with the vertices of strong forces. The details of the PNC studies were reviewed, for example, in Refs. [39, 40, 41, 42]. The current problem is originated from the fact that weak meson-nucleon coupling constants deduced from various PNC experiments are not consistent. Haxton et al., [43] concluded that the experimental PNC results are still not satisfactory and more experimental as well as theoretical studies are needed.

Common methods of experimental PNC studies are to measure the parity mixing between the parity-doublet states. In the traditional experiment, one of the doublet levels is excited in the nuclear reaction. Then, the PNC effect is appeared as the asymmetry of emitted circularly polarized photons. Emitted circularly polarized photons are very difficult to be correctly measured.

Recently, we propose a new method for measuring the PNC effect in nuclei by measuring the excitation and de-excitation of the parity doublets using NRF [44, 45]. Let us consider electromagnetic excitation and decay of the lowest excited $1/2^-$ (E_x=109.9 keV) state in ^{19}F, for an example. It is assumed that the ground state with $J^\pi = 1/2^+$ and the first excited state with $1/2^-$ are the parity doublet. In this case, the first $1/2^-$ (E_x=109.9 keV) state in ^{19}F is excited by NRF. In the previous experiments for the circular polarization measurement of emitted γ-rays, one of the doublet levels was excited via a nuclear reaction, and the admixture of the configuration of the opposite parity was manifested as the asymmetry A_γ of γ-rays emitted from the excited states with a polarization, or

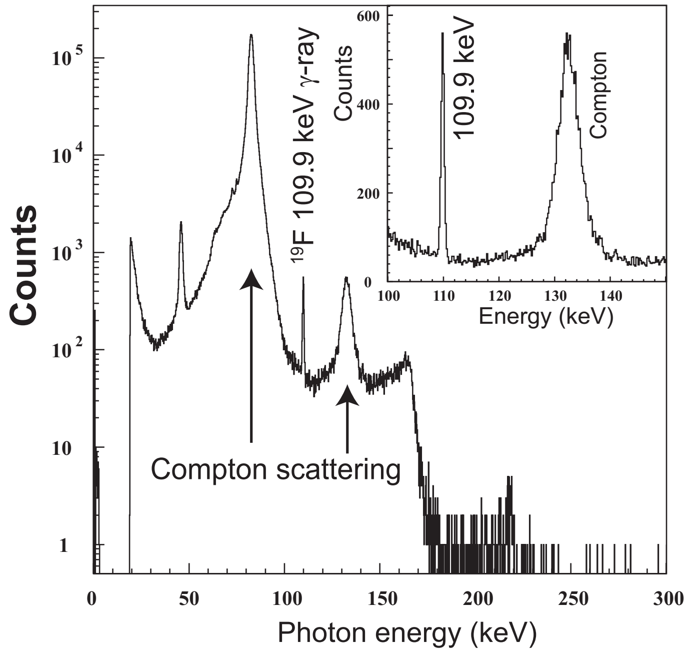

Figure 7: Photon spectrum to demonstrate the nuclear resonance fluorescence γ-rays from the 109.9 keV level in ^{19}F. A 110 keV Wigger photon beam with an energy resolution of about 100 eV has been used at SPring-8.

as the circular polarization P_γ of γ-rays emitted from unpolarized excited states. In the case of the $1/2^- \to 1/2^+$ transition in ^{19}F, the PNC value is reported as -8.5×10^{-5} [46] with 30% error bar. In case of ^{19}F, a high intensity photon source from the synchrotron radiation facilities at SPring-8, ESRF, and APS is available for the PNC measurement. At SPring-8, the intensity from a Wiggler system reaches at 10^{13} photons/second at $E =$ 109.9 keV with an energy width of about 0.1 keV. The NRF events for exciting the 109.9 keV $1/2^-$ state are expected to be around 10^8 /second for the LiF target with a thickness of 0.5 cm. This NRF event rate is high enough to examine the theoretical formula presented in the present work..

Figure 7 shows a sample NRF spectrum measured with a Ge detector at SPring-8 using a Wigller beam [47]. A strong excitation of the $1/2^-$ 109.9 keV level in ^{19}F is demonstrated. The accuracy of the measurement depends on the details of the experimental set-up (counting rates, detection solid angles etc.). According to our estimation we expect to achieve the accuracy better than 10-20% for one week measurement, which exceeds considerably the previous experiments in the traditional design. A serious difficulty stems from a high counting ratio of the Compton scattered γ-rays as backgrounds. One method to overcome this problem is to use a multi-segmented detector in order to greatly reduce the counting rate of each detector and obtain the necessary total counts of 10^{10} as the NRF events. The use of newly developed lutetium oxyorthosilicate (Lu_2SiO_5, LSO) and lutetium-yttrium oxyorthosilicate ($Lu_{2(1-x)}Y_{2x}SiO_5$, LYSO) crystals with a decay constant of about 40 ns and an energy resolution of 7-10% is also promising for the NRF measurement with a high-counting rate. Another way is to obtain a photon beam with an ultra high resolution of $\Delta E/E = 10^{-5}\sim10^{-6}$. In this case, the background photons due to Compton scattering are greatly reduced, and the γ-ray events due to the NRF process are relatively enhanced to get a high counting rate necessary for performing a high-statics PNC measurement.

If a high-energy photon beam with a high-intensity stronger than 10^8 /second will be realized in near future, the following experiments with NRF, which have been difficult to be performed due to the lack of intensity, are feasible. The NRF process is only favorable to excite with the E1 and M1 modes. With linear polarized photons, E1 and M1 excitations are determined without any theoretical ambiguities. Samples of such experiments are relevant to

1. the transitions between the octupole-deformed states with the same spin and with different parities in the mass of about 180,
2. the collective excitations of scissor or troidal modes in medium-heavy nuclei,
3. photo-nuclear fission
4. $E1$ and $M1$ excitations near the particle emission thresholds for the network calculations in astrophysics.

For this purpose, we need to obtain the γ-ray beam with an energy higher than several MeV, which is only successful with the inverse Compton process. There are additional important studies that are relevant to the nuclear transmutation with (γ,n) reactions, the materials science with polarized positrons, the Mössbauer effect measurements with the NRF photons, and the medical application of the high-intensity photons.

4 Summary and final remarks

Thanks to the recent laser and accelerator technologies, it is turned out that photon beams in the energy range from sub-MeV to a few GeV become usable for various scientific developments. The subjects to be studied with such photon beams are

1. astrophysics applications of nuclear physics to draw the story of nuclear synthesis in the universe,
2. nuclear and hadron structures with high intensity and high polarization photon beams,
3. studies of basic symmetries in the nuclear and atomic processes,
4. feasibility studies of nuclear transmutation technologies with high-intensity photon beams in the energy range of 10-30 MeV,
5. application of polarized photon beams to generate polarized positrons, which are useful for materials science developments,
6. new technologies to generate the high intensity MeV photons with a full usage of the quantum effect of coherency.

Recently, in Japan, South-Korea, China, Taiwan, US, and EU countries, many scientists discuss to install the beam lines for inverse Compton scattering at the SR facilities. There are great possibilities of having a high-intensity photon beam due to the boson nature of light, which is not fully used in the past.

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