4. Nuclear Physics Using Electron Beams

TAMAE Tadaaki
Laboratory of Nuclear Science, Tohoku University, Mikamine, Taihaku-ku,
Sendai 982-0826, Japan

(Received 13 August 2001)

Abstract
Experiments using electron beams are briefly described. A high-intensity pulsed beam is usable for single-arm experiments, while a continuous beam is necessary for coincidence experiments. As photons induced with a monochromatic electron beam have a continuous energy-spectrum, the energy of the scattered electron is measured in order to fix the photon energy, if it is possible. When the energy of the scattered electron cannot be measured, the reaction cross section is unfolded from series of measurements at different incident electron energies. As examples of the experiments, elastic electron scattering and photonuclear reactions in the giant resonance region are described. Recent investigations of the photonuclear reactions at low energies are also presented, and possible contributions of laser-nuclear physics are suggested.

Keywords: photonuclear reaction, electron scattering, pulsed beam, continuous beam, charge distribution, giant resonance, double giant resonance, laser-induced Compton back-scattered γ-ray facility, low-energy photonuclear reaction

4.1 Introduction
Electromagnetic probes like the electron and the photon are powerful to study nuclei because their interaction is well understood and weak enough to use a perturbative approach. Photonuclear reactions have been studied extensively since Baldwin and Klaiber first observed a resonance-like structure in the photo-fission and (γ, n) reactions [1]. Shortly after the experiments, Goldhaber and Teller proposed to interpret the structure as the giant dipole resonance [2], and the photonuclear reactions became the most powerful tool for investigation of the nuclear reaction. On the other hand, electron scattering is the best tool for precise investigation of the nuclear structure. The first electron scattering to measure the nuclear size was performed 50 years ago. Pioneering experiments of Hofstadter (1961 Nobel Prize winner) in 1950's established the power of electron scattering for investigation of the charge distribution of nuclei. They first revealed the finite size of the proton [3]. Electron scattering has also exhibited its power to investigate the momentum distribution of protons in nuclei [4].

In the first approximation, the nucleus consists of protons and neutrons. It is well known that the nuclear force is associated with exchange of mesons between nucleons. Mesons in the nucleus are directly observed as the Meson Exchange Currents (MEC). The role of MEC and the isobar current, and the question of relativistic corrections have come into focus recently. Moreover, search of the quark effects or QCD effects in the nucleus is a present frontier of nuclear physics.

4.2 Electron Accelerator Facilities
Electrons are accelerated with linear or circular
accelerators. Conventional accelerators for the electron are a linear accelerator (linac) and a synchrotron. In the linac, electrons are accelerated with periodic and oscillating electric field in cavities distributed on the straight, excited by radio-frequency power supplies. The intensity of the extracted beam from the linac is much stronger than that from the synchrotron. The linac is, therefore, more useful for nuclear physics. Several electron linacs for nuclear physics were constructed around 1970 in USA, France, Germany, Holland, and also Japan. A 300 MeV electron linac in Tohoku University was constructed in 1967, and the giant quadrupole resonance was first found there [5]. Experiments of electron scattering and photonuclear reactions were very active in 1970's. The beam of the electron linac is of very high current, but the conventional-type electron linac could accelerate only a short-pulsed beam owing to large power loss of microwave in the cavities. In addition, the operation costs of the linac are high at higher energies. The synchrotron, which is a circular accelerator, accelerates electrons up to high energies by accelerating them repeatedly in relatively weak electric field. The operation costs are lower compared to the linac, and synchrotrons were used at higher energies or for experiments which needs longer pulsed beams.

In 1980's, experiments shifted from single-arm experiments, where only one particle is detected at once, to coincidence experiments. In the coincidence experiments, where correlated particles are detected in coincidence, the pulsed beam is not preferable, because it happens more frequently that uncorrelated particles are detected accidentally. Continuous beam accelerators such as a pulse-stretcher, a microtron, and a superconducting linac have been constructed since 1980's. Tohoku University constructed a world-first 150 MeV pulse stretcher ring (SSTR) [6] in 1981. The pulse stretcher ring accepts a pulsed beam from an electron linac and converts it to a continuous beam by extracting electrons slowly. After its success, four pulse stretcher rings were constructed at Saskatchewan in Canada, NIKHEF-K in Holland, MIT-Bates in USA, and Tohoku University again. The microtron raises the beam energy in step by recirculating the electron several tens of turns through a relatively low-gradient accelerating section. An 850 MeV microtron at Mainz in Germany has proved its usefulness for nuclear physics. A superconducting linac, which suppresses power loss of microwave in the cavity, allows a high duty operation. After construction of several low-energy superconducting accelerators, a 4 GeV (improved to 6 GeV recently) superconducting recirculator at Jefferson Laboratory in USA has opened the new era of Hadron Physics.

A storage ring operated as a synchrotron light facility is usable also for nuclear physics. High energy γ-rays produced by backward Compton scattering of laser light with high-energy electrons stored in the ring are available. A big advantage of this method is that polarized γ-rays can be obtained easily at existing synchrotron light facilities. At Spring-8 in Hyogo Prefecture, experiments using polarized gamma rays of 2.4 GeV at maximum have been started [7].

4.3 Electron Scattering and Photo-Reaction

In the electromagnetic interaction, the nucleus is excited with real or virtual photons. Several methods of the experiments are shown in Fig. 1. In the photonuclear reaction (Fig. 1 (a) (b) (c)), real photons irradiated with an electron beam excite the nucleus, where the momentum q transferred by the photon is constrained to the energy q as q = ω. In electron scattering (Fig. 1 (d)), on the other hand, the virtual photon exchanged between

![Diagram of electron scattering and photo-reaction](image-url)
an electron and a nucleus excites the nucleus, where the transferred momentum $q$ can be changed independent of the transferred energy $\omega$ in the region $q > \omega$. Energy spectra of the real or virtual photons are continuous over wide range of energies. In the bremsstrahlung experiments (Fig. 1 (a)) and the electro-disintegration (Fig. 1 (e)), the emitted particles are observed but no scattered electron is detected. In such cases, observed particles are products by photons of a wide energy spectrum; an energy-spectrum of the emitted particle, $d\sigma(E_e)/dE_p$, measured with an electron of an energy of $E_e$, is related with a spectrum, $d\sigma(E_y)/dE_p$, with a photon of energy $E_y$, as

\[
\frac{d\sigma(E_e)}{dE_p} = \int_0^{E_e} \frac{d\sigma(E_y)}{dE_p} N(E_e, E_y) dE_y, \tag{1}
\]

where $N(E_e, E_y)$ is the number of photons with an energy of $E_y$ per unit energy induced an electron with an energy of $E_e$. The spectra for defined photon energies, $d\sigma(E_y)/dE_p$, are more meaningful for nuclear physics. The equation can be unfolded [8-10] for $d\sigma(E_y)/dE_p$ using measured $d\sigma(E_e)/dE_p$ at different energies, using $N(E_e, E_y)$ of the real [11,12] or virtual [13] photons calculated in QED. Direct determination of the photon energy is due to measurement of the scattered electron energy. In electron scattering, the virtual-photon energy is determined by measuring the energy $E_e$ of the scattered electron using the relation: $\omega = E_e - E_y$, where $E_e$ is the energy of the incident electron (Fig. 1 (d) (f)).

Also in the photonuclear reaction, the energy of the photon can be determined by measuring the scattered electron (tagged-photon technique) (Fig. 1 (b)). In laser-induced Compton back-scattered $\gamma$-ray experiments (Fig. 1 (c)), the energy $E_y$ of the scattered photon depends on its angle $\theta_y$ with respect to the direction of the incident electron; the angular dependence is shown in Fig. 2 for $E_e = 1$ and $8$ GeV. As shown in the figure, the photons are scattered at very forward angles at higher electron energies. The photon energy can be determined by collimating the photons for low energy electron beams. However, the tagged photon system is necessary for electron energies higher than 2 GeV because the opening angle of the photons is too small to fix their energies by collimation. The use of a positron beam is another technique for obtaining monochromatic $\gamma$-rays. A positron with an energy of $E_{e^+}$, striking a thin target and annihilating with an electron in the target, produces two photons; the energy of one photon is $E_{e^+} + \frac{1}{2} m_e$ and the other $\frac{1}{2} m_e$ when they are emitted to the direction of the incident positron. The higher-energy one was used for compilation of the $(\gamma, n)$ cross section in the giant resonance region for many nuclei, which were performed at Saclay in France and Livermore in USA in 1970’s [14].

### 4.3.1 Charge and magnetic density distributions

As the electron has charge, it interacts with charge as well as currents and magnetization in the nucleus. Electron scattering is most reliable procedure to measure charge distribution of the nucleus. In Fig. 3 charge densities for all doubly closed shell nuclei are compared with the mean-field predictions [4]. Although the experimental charge densities are broadly described by the theory, they clearly show that there is a discrepancy between experiments and calculations in the nuclear interior. The detailed study of the interior of the charge
density is demonstrated in Fig. 4: the difference between $^{206}\text{Pb}$ and $^{205}\text{Tl}$, which gives a direct information of the 3s proton orbit [15]. The charge density of the 3s proton obtained in this experiment shows usefulness of the mean-field theory, however, a discrepancy in the interior region suggests demands beyond the mean-field theory, such as nucleon-nucleon correlations. In stable nuclei, the bulk of the proton and the neutron is same. However, the neutron distribution extends out the proton bulk in some unstable nuclei as shown in Fig. 5: the neutron halo and the neutron skin. Modification of the proton distribution is also expected in such nuclei. Measurement of the proton distribution in unstable nuclei is planned in RI Beam Factory in RIKEN.

There exists magnetization in nuclei with none-zero spin. Two identical nucleons cancel their spin by making a pair, and valence nucleons are source of magnetization of the nucleus. Magnetization distributions have been investigated in many nuclei [16,17]. They have produced a great progress such as the core polarization (deformation of the core due to a valence nucleon) and meson exchange currents.

4.3.2 Electron scattering for few-body nuclei

Two- and three-body systems are especially important to clarify non-nucleonic degrees of freedom such as meson-exchange currents, $\Delta$ isobars and relativistic effects, because their ground-state wave functions may be calculated exactly for given nucleon-
nucleon potentials. Our recent measurement [18] of elastic magnetic form factor of $^3\text{He}$ extended up to 1.7 (GeV/c)$^2$ has demonstrated that no existing non-relativistic theoretical calculation satisfactorily accounts for all the available data of the three-body systems, and suggested the need of consistent relativistic treatments for both the wave function and the operator, and perhaps, the inclusion of quark-gluon dynamics. Recent measurement of the deuteron form factor at Jefferson Lab [19] showed it appears to follow the prediction of perturbative QCD above 2 (GeV/c)$^2$, while the prediction fails to reproduce the tensor polarization $t_{20}$ below 1.7 (GeV/c)$^2$ [20]. Future experiments in few-body nuclei are expected to open new frontiers of nuclear physics.

4.3.3 Giant resonance

Giant resonances are the collective vibrational excitation of protons against neutrons [2]. In the photonuclear reaction, the electric dipole (E1) giant resonance (GDR) is the most important and has been systematically investigated, because it dominates the reaction cross section [14]. The photo-neutron cross section of $^{238}\text{U}$ is shown, as an example, in Fig. 6. The resonance energy $E$ varies smoothly with mass number $A$ according to the law that can be well approximated by $E = 78 A^{-1/3}$ or $34 A^{-1/6}$ MeV [21]. The sum of the E1 strength from a state to all other states is expressed in a simple form, known as the Thomas-Reich-Kuhn sum rule. The photonuclear cross section exhausts near 200% of the sum rule. The excess is attributed of meson-exchange currents, where the photon couples with charged mesons in flight between the neutron and the proton. The GDR decays mainly through neutron- or proton-emission in light and medium weight nuclei. In heavy nuclei the decay of the GDR is dominated by neutron emission because the Coulomb suppression is strong for proton emission. The mechanism of the neutron- and proton-emission is different from each other in heavy nuclei. Figures 7 and 8 show neutron and proton energy spectra. The neutron spectrum has a maximum around 1 MeV and rapidly decreases with higher energies [22]. The spectrum is well reproduced with statistical calculations. On the other hand, the proton energy spectrum has its peak around 10 MeV because the emission of lower energetic protons is suppressed with the Coulomb barrier; the statistical contribution to the proton emission from $^{197}\text{Au}$ is less than 1%. The detailed description of the proton emission from heavy nuclei is presented in Ref. [10].

One of the most exciting progresses in the field of giant resonances in atomic nuclei over the last fifteen years was the experimental observation of two-phonon giant resonances; they were first observed in pion double charge exchange [23] and heavy-ion reactions (Fig. 9) [24]. The observed excitation energy of the new resonance is about twice as high compared to the energy of the GDR, and it is called the Double Giant Dipole Resonance (DGDR) because it is interpreted as a GDR built on a GDR. The DGDR has the $J^\pi = 0^+$ and $2^+$...
components. As both of these multipolarities can be excited weakly in the photonuclear reaction, it has never been observed in the reaction. Recently, Suzuki [25] suggested opportunity of a double giant resonance composed of the GDR and the GQR (Giant Quadrupole Resonance). It may be excited with photons via meson exchange currents, because it has the \( \mathcal{F} = 1^- \) component, which is dominant in the photonuclear reaction.

Fig. 8 (a) Spectrum of the artificially-constructed quasi-monochromatic photons. It was constructed with four virtual-photon spectra at \( E_\gamma = 29, 25, 21 \) and 17 MeV. (b) Photo-proton energy-spectrum corresponding to artificially-constructed quasi-monochromatic photons at \( E_\gamma = 26.22 \) MeV. Theoretical calculations in the shell model are shown by histograms [10].

4.4 Low Energy Photonuclear Reaction and Nuclear Physics with Laser Beam

Astrophysical processes most often involve radiative capture reactions at low energies. Research of such processes is important to explore nucleosynthesis in stellar evolution, supernovae and a big bang. It also provides fundamental data for investigations of neutrino oscillation. However, the cross sections of such reactions decrease exponentially with decreasing energy, making their experiments extremely difficult. The reverse reaction of the radiative capture at low energies is the photonuclear reaction near the reaction threshold, which can give us the same information. Measurements of the photonuclear reaction are preferable in special cases such as the \( n + ^4\text{He} + ^4\text{He} \rightarrow \gamma + ^8\text{Be} \) reaction, which bridges mass gap of \( A = 5 \) and 9 in core-collapse supernovae. In this case the reverse reaction \( \gamma + ^8\text{Be} \rightarrow n + ^4\text{He} + ^4\text{He} \) is much easier to be performed. Another advantage is that the use of linearly-polarized \( \gamma \)-rays makes a separation of \( E1 \) and \( M1 \) transitions possible. Such experiment [26] has been performed recently using laser-induced Compton back-scattered \( \gamma \)-rays in the storage ring TERAS of the Electrotechnical Laboratory (ETL).

The photon beam flux in existing laser-induced Compton back-scattered \( \gamma \)-ray facilities is about \( 10^7 \gamma/s \). The High-Intensity Gamma-ray Source project (HIGS) at Duke University Free Electron Laser Laboratory [27] has produced a higher intensity of flux using a storage-ring-driven free-electron laser light. The first experiment at this facility, a measurement of the near-threshold

Fig. 9 Cross section of \( \text{Pb} \) excited with bombardment of \(^{136}\text{Xe} \). The resonance energies for the one- and two-phonon giant dipole resonances and for the isoscalar and isovector quadrupole resonances are indicated. The bump at 30 MeV corresponds to the DGDR (figure from ref. [24]).
2H(γ, n)p analyzing power, has been performed recently [28]. Upgrade of the facility which is under way will improve the flux intensity to 10^9γ/s with an energy spread of 1%. The facility aims fundamental studies in nuclear physics, especially topics related to astrophysics.

Recently nuclear reactions have been observed in reactions using ultra-high power laser beams [29,30]. Most of these experimental data can be described with existing nuclear data. Can the laser nuclear physics be a new physics? It may contribute for the photonuclear reactions at low energies above-mentioned, as a strong γ-ray flux created with ultra-high power laser is suitable for measurements of very small cross sections. In order to obtain new information, however, experiments must be performed under well-controlled conditions as to the energy, the energy resolution, the beam intensity, and the target thickness, as experiments in nuclear physics are. Quality of experiments at the HIGS facility will give a new standard for experiments at low energies. Detection of emitted particles with very low energies is also necessary. Development of new detectors and techniques for analysis must be new challenges in this field.

References
[14] See, for example, B.L. Berman and S.C. Fultz, Rev. Mod. Phys. 47, 713 (1975).