Feasibility of measurement of the electromagnetic polarizability of the bound nucleon

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It is shown that the differential cross section for Compton scattering of 25–100 MeV photons on Pb through $\theta=30°$ is very sensitive to the polarizability of the bound nucleon. A first experiment led to $1.2^{+0.4}_{-0.3}$ times the free-nucleon value.

The advent of cw currents of electrons by which high-intensity beams of "tagged" photons can be produced makes nuclear Compton (elastic photon) scattering an interesting tool in intermediate-energy nuclear physics. Recent surveys[1,2] have drawn attention to different potentialities contained in this technique. In this paper we report about a first successful small-angle Compton-scattering experiment carried out on a heavy nucleus using the tagged-photon beam of the new 180 MeV accelerator MAMI A in Mainz. The motivation for this experiment was to explore the possibility of a direct determination of the bound-nucleon electromagnetic (em) polarizability, via Compton scattering at energies below the pion threshold. Although the sum of the electric and magnetic polarizabilities $\bar{\alpha}_N+\bar{\beta}_N$ is given by the absorption cross section through the zero-energy limit of the dispersion integral,[3,4] i.e.,

$$A(\bar{\alpha}_N+\bar{\beta}_N)=\frac{1}{2\pi^2}\lim_{\omega\to 0}\int_{m_\pi}^{\infty}\frac{\sigma_A(\omega')-\sigma_{\rm QD}(\omega')}{\omega'^2-\omega^2}d\omega' \qquad (1)$$

(σ_A is the total; $\sigma_{\rm QD}$ is the quasideuteron absorption cross section), a direct measurement of $\bar{\alpha}_N+\bar{\beta}_N$ is highly desirable. Arguments are as follows: (i) For a calculation of $\bar{\alpha}_N+\bar{\beta}_N$ through (1) the nuclear photoabsorption cross section has to be known up to above 2 GeV. This is the case only if use is made of the scaling of absorption cross sections with mass number A, so that data obtained for different nuclei may supplement each other.[5] For individual nuclei the absorption data are incomplete and partly controversial. For Pb, data exist below[6] 513 MeV and above[7] 1.7 GeV. (ii) Nuclear photoabsorption measurements are carried out either by measuring the total absorption cross section and subtracting the calculated pair-production cross section,[8] or by measuring nuclear partial cross sections and extrapolating towards the total nuclear absorption cross section.[6] Both methods may contain systematic errors, whereas in a nuclear Compton-scattering experiment beam intensity and scattering rate are measured with the same detector and no additional information is necessary to determine the elastic differential cross section. One drawback, however, is that the scattering amplitude is a superposition of different partial amplitudes which must be disentangled by varying the scattering angle and the photon energy.

Experimental data of good precision are available only for the proton. The em polarizability of the proton $\bar{\alpha}_P+\bar{\beta}_P=(14.2\pm0.2)\times10^{-4}$ fm^3 as derived from photoabsorption data has been partitioned into $\bar{\alpha}_P=(11.3\pm2.5)\times10^{-4}$ fm^3 and $\bar{\beta}_P=(2.9\pm2.5)\times10^{-4}$ fm^3 using Compton-scattering data.[9] Thus, the polarizability is predominantly electric, although the Δ resonance is the most prominent structure above pion threshold and the separate application of the dispersion integral to the $E1$ and $M1$ partial cross sections[2,8,10] leads to equal numbers for $\bar{\alpha}_P$ and $\bar{\beta}_P$. This finding shows that retardation and diamagnetic corrections are important. At energies above the meson threshold, predictions of proton Compton amplitudes based on dispersion relations lead to a reasonable fit to the majority of the data.[11,12] However, in the maximum of the Δ resonance there is a remarkable discrepancy which has to be clarified in future experiments.

Calculations carried out in quark models[13–15] have reproduced the experimental data for $\bar{\alpha}_P$ and $\bar{\beta}_P$ with an accuracy of 30% or better. In this framework it has been emphasized in Ref. 13 that it would be highly interesting to deduce the polarizability of nucleons bound in nuclei, e.g., from Compton-scattering data for energies just below the pion production threshold. Since the polarizability is proportional to the cube of the bag radius,[13] it can be regarded as a measure of the size of the bag. From the ratio

$$(\bar{\alpha}_N+\bar{\beta}_N)_{\rm bound}/(\bar{\alpha}_N+\bar{\beta}_N)_{\rm free} \qquad (2)$$

one could then read off whether nucleon bags are larger in nuclei as suggested by the European Muon Collaboration (EMC) effect.

We have chosen to carry out the proposed[2,13] experiment on Pb at an angle of 30° for the following reasons. (i) Model calculations show that the elastic differential cross section of Pb is most sensitive to the em polarizability at a scattering angle of $\theta=30°$ and almost insensitive at large angles. (ii) Pb is the complex nucleus which has been most precisely investigated by photoabsorption[16] and photon-scattering[17] experiments carried out at $\theta\geq60°$. Therefore, it is well known how to analyze the data. The procedure is as follows. The total scattering amplitude $f_{\rm tot}$ is a coherent superposition of the nuclear scattering amplitude f_A and the Delbrück amplitude f_D, i.e.,

$$f_{\rm tot}(\omega,\theta)=f_A(\omega,\theta)+f_D(\omega,\theta) \ . \qquad (3)$$

The nuclear scattering amplitude itself is a coherent superposition of the modified Thomson amplitude (nonresonant exchange term)[2]

$$R_{\rm NR}(\omega,\theta)=\frac{e^2}{M}\left[(1+\varkappa_{\rm res})\frac{NZ}{A}-ZF_z(q)-\varkappa_{\rm res}\frac{NZ}{A}F_{\rm ex}(q)\right]\boldsymbol{\epsilon}'\cdot\boldsymbol{\epsilon} \ , \qquad (4)$$

the resonance amplitudes[2] $R_{\rm res}(\omega,\theta)$ for the scattering through giant resonances and the quasideuteron effect, and the amplitude $N(\omega,\theta)$ for scattering through the bound-nucleon polarizability, i.e.,

$$f_A(\omega,\theta)=R_{\rm NR}(\omega,\theta)+R_{\rm res}(\omega,\theta)+N(\omega,\theta) \ . \qquad (5)$$

In (4) e^2/M is the classical nucleon radius, $\varkappa_{\rm res}$ is the enhancement factor of the integrated strength located in the giant-dipole resonance (GDR), $F_z(q)$ is the charge form factor of the nucleus, $F_{\rm ex}(q)$ is a form factor related to the spatial distribution of the correlated proton-neutron pairs, and $\boldsymbol{\epsilon}$ and $\boldsymbol{\epsilon}'$ are the polarization vectors of the ingoing and outgoing photon, respectively. Large angle ($\theta\geq 60°$) Compton-scattering cross sections[2,17] are very sensitive to the form factors in (4) and, therefore, are capable of determining the Woods-Saxon half-width radius $C_{\rm ex}$, which is related to $F_{\rm ex}(q)$. Taking $\varkappa_{\rm res}=0.216$ from photoabsorption[16] and photon-scattering data measured in the GDR energy region,[17] and $C_z=6.62$ fm from elastic electron scattering data, $C_{\rm ex}\approx 4$ fm is obtained. At $\theta=30°$ the dependence of $R_{\rm NR}(\omega,\theta)$ on the form factor is small. Therefore, predictions with very high precision can be made for $R_{\rm NR}(\omega,\theta)$ at this angle. The resonance amplitudes $R_{\rm res}$ entering into (5) are calculated for the forward direction from the well-known photoabsorption cross sections using the optical theorem and the once subtracted dispersion relation. It is then adapted to larger angles by making use of the angular distribution functions for the different multipolarities. In addition, the quasideuteron part of $R_{\rm res}$ has to be multiplied by $F_{\rm ex}(q)$ because for this mode of excitation the different volume elements of the nucleus act as independent radiators.

Compton scattering by the free proton for energies below pion threshold and explicit expressions for the scattering amplitudes are discussed in Ref. 9. We adapt these expressions to nucleons bound in a spin-saturated nucleus, assuming that effects from the anomalous magnetic moment and from relativistic and recoil corrections are not important. The following expression for the amplitude describing the scattering through the bound-nucleon polarizability is obtained:

$$N(\omega,\theta)=A\omega^2(\bar\alpha_N\pm\bar\beta_N)\left[1+\frac{\omega^2}{\varpi^2}\right]F_m(q)\frac{\cos\theta\pm 1}{2} \ . \qquad (6)$$

In (6) the upper signs stand for the helicity-nonflip amplitude which is the relevant one at small angles, and the lower sign stands for the helicity-flip amplitude. The term $1+\omega^2/\varpi^2$ represents the $0(\omega^2)$ term of a series expansion of the dispersion integral in (1) and $F_m(q)$ a form factor related to the distribution of nucleons in the nucleus. An estimate of ϖ may be obtained by inserting the photoabsorption cross sections $\sigma_A(\omega)$ and $\sigma_{\rm QD}(\omega)$ into the dispersion integral displayed in (1), leading to $\varpi=(270\pm20)$ MeV. The $0(\omega^2)$ correction obtained in this way amounts to only $(9\pm1)\%$ at 80 MeV. The quantity $F_m(q)$ may be identified with $F_z(q)$ without loss of accuracy in the evaluation of $\bar\alpha_N+\bar\beta_N$ from (6).

The experiments have been carried out using the tagging facility installed by the Max-Planck-Institut für Chemie at the cw accelerator MAMI A at Mainz. For a heavy nucleus like Pb, the smallest angle where intermediate-energy photon scattering has successfully been observed[2,17] was $\theta=60°$. This limitation was due to the electromagnetic background produced in the scattering target. The progress achieved in this experiment was due to the continuous current of the new accelerator which made coincidence techniques possible. The production of bremsstrahlung in the scatterer was kept small by using a thin 595 mg/cm^2 Pb scatterer. The large amount of electron-positron pairs leaving the scatterer was effectively suppressed by veto counters in front of the collimators of the NaI detectors. Spectra obtained by this technique at a tagged photon energy of (32.4 ± 0.5) MeV and scattering angles of 15° and 30° are shown in Fig. 1. The detector sizes at these two angles were 16 cm $\times$ 16 cm $\times$ 24 cm and 25 cm diam $\times$ 25 cm, respectively. The total beam time amounted to 100 h. In order to separate background from elastic scattering events, a

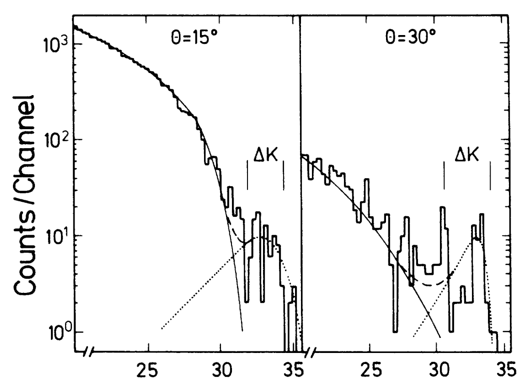

FIG. 1. Spectra of photons obtained for a primary energy of $\omega=32.4\pm0.5$ MeV. Solid lines: calculated background, mainly due to bremsstrahlung produced in the scattering target. Dotted lines: response functions of the detectors, measured with the detectors in the direct beam and adapted to the spectrum of elastically scattered photons. Dashed-dotted line: sum of solid and dotted lines.

Monte Carlo program was developed by which the spectrum of photons and of electrons and positrons leaving the scatterer and entering the solid angles subtended by the NaI detectors was calculated on an absolute scale. This Monte Carlo program was based on the program of Corvisiero *et al.*[18] and adapted to the present problem. This adaptation was necessary because background production at angles of 15°–30° with respect to the direct beam is dominated by the rare events of a shower. Therefore, by using the shower codes without adaptation, prohibitive computer time would have been necessary. It turned out that the largest part of the measured background was due to bremsstrahlung produced in the scattering foil, whereas electron-positron pairs entering the solid angles subtended by the detectors were rejected by the veto counters with an efficiency larger than 99.9%. The result of the background simulation is depicted by the solid curves. The dotted curves show the detector response functions, measured when the detectors were placed in the direct beam and normalized to the number of elastically scattered events. The dashed line represents the sum of background and detector response function. Above the background there is a range of energies (ΔK in Fig. 1) in which the rate of elastically scattered photons can be determined without ambiguity. By the following arguments it can be shown that there were no pileup events in ΔK: (i) Above the energy range where events of elastically scattered photons were expected, the difference between the true-plus-random and random events measured with the tagging system was zero within the statistical errors. (ii) Computer simulation of pileup was carried out, confirming that there was no significant pileup. A significant branching of inelastic scattering into the first excited states of the nuclei ^{206}Pb and ^{208}Pb appears to be unlikely due to the following arguments: (i) An experiment carried out on these nuclei up to 30 MeV did not reveal any inelastic component.[19] (ii) For energies between 30 MeV and the pion threshold no predictions of inelastic scattering exist for these nuclei, but from findings at higher energies[20] it may be expected that inelastic scattering increases with increasing scattering angle. However, no indications of inelastic scattering have been observed in large-angle photon-scattering experiments[17] carried out on Pb, where differential cross sections measured with different energy resolution, i.e., by using bremsstrahlung and positron-annihilation photons, have been compared with each other. Therefore, we tentatively assume that the indications for inelastic scattering contained in the data of Fig. 1 are mostly due to the limited statistical accuracy. Experiments are in preparation which are designed to clarify this point.

Differential cross sections evaluated from the elastic scattering data are shown in Fig. 2. The data points are averages over five successive intervals of 1 MeV width. At $\theta=15°$ the dominant contribution to the elastic differential cross section stems from Delbrück (D) scattering i.e., from scattering through virtual pair production in the Coulomb field of the nucleus. Therefore, at this angle the existing predictions were tested in order to arrive at reliable D corrections for the data at $\theta=30°$. It was found that the D amplitudes based on the exact eval-

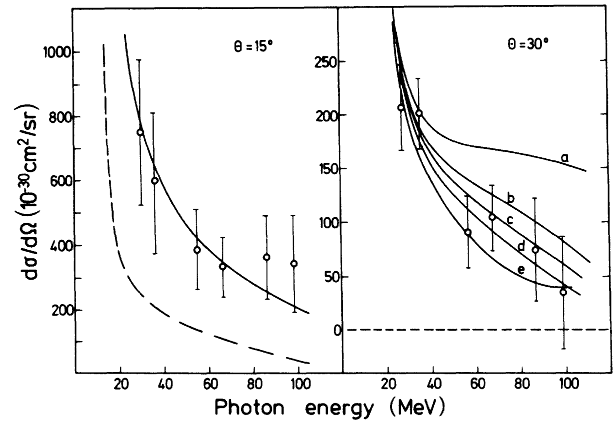

FIG. 2. Differential cross sections for elastic photon scattering by Pb compared with different predictions. For $\theta=15°$: solid : superposition of nuclear scattering and D scattering calculated from the LOF. Dashed : nuclear scattering only. For $\theta=30°$: superposition of D scattering and nuclear scattering calculated using $\bar{\alpha}_N+\bar{\beta}_N$ as a parameter. a, $\bar{\alpha}+\bar{\beta}=0$; b, $\bar{\alpha}+\bar{\beta}=10$; c, $\bar{\alpha}+\bar{\beta}=15$; d, $\bar{\alpha}+\bar{\beta}=20$; e, $\bar{\alpha}+\bar{\beta}=30$ (in units of 10^{-4} fm^3).

uation of the lowest order Feynman (LOF) graph provided a good fit to the data (solid curve at $\theta=15°$) whereas predictions of the impact factor method (IFM) proved to be less reliable in this energy range.[21] It might be suspected that because of the high Z of the scattering target, Coulomb corrections to the LOF predictions may be substantial, but not perceptible in the $\theta=15°$ data. Because of the very strong forward peaking of D scattering, the D correction is very small at $\theta=30°$. Therefore, any possible uncertainty in the D amplitudes at $\theta=30°$ is insignificant for the predicted elastic differential cross sections.

The data at $\theta=30°$ are very sensitive to the em polarizability of the nucleon inside the nucleus. This is clearly seen from curves a–e in Fig. 2 which have been calculated using the em polarizability of the nucleon as a parameter. Applying a least-squares procedure, we arrive at

$$(\bar{\alpha}_N+\bar{\beta}_N)_{\text{bound}}=(19^{+6}_{-5})\times 10^{-4}\ \text{fm}^3\ . \tag{7}$$

This value is larger than the em polarizability of the free proton $\bar{\alpha}_P+\bar{\beta}_P=14.2\times 10^{-4}$ fm^3 by one standard deviation. The difference becomes slightly smaller when taking into account that the polarizability of the free neutron is somewhat larger. Then, the average over 82 protons and 126 neutrons is given by[4]

$$(\bar{\alpha}_N+\bar{\beta}_N)_{\text{free}}=15.5\times 10^{-4}\ \text{fm}^3\ . \tag{8}$$

For comparison with the bound-nucleon em polarizability as obtained from Compton scattering we have carried out a careful reanalysis of the dispersion integral (1). Interpolating between existing experimental photoabsorption cross sections[6,7] of Pb by using data obtained from Cu via A scaling,[5] taking into account an A-dependent shadowing correction, and subtracting an extrapolation of the quasideuteron (QD) cross section, a bound-nucleon em polarizability of

$$(\tilde{\alpha}_N+\tilde{\beta}_N)_{\text{bound}}=(13.2\pm0.4)\times10^{-4}\ \text{fm}^3 \tag{9}$$

is obtained. The error given in (9) includes uncertainties from the extrapolated QD effect due to different parametrizations, uncertainties due to shadowing, the statistical error of the Pb data, and uncertainties in the interpolation, but disregards possible systematic errors. For instance, if we neglect the QD subtraction completely, an increase of $\tilde{\alpha}_N+\tilde{\beta}_N$ by 1.7×10^{-4} fm^3 is obtained. We leave it as an open problem that the bound-nucleon polarizabilities of (7) and (9) deviate from each other by one standard deviation.

Our bound-nucleon em polarizability of (7) is a factor of $1.2^{+0.4}_{-0.3}$ larger than the proton-neutron average free-nucleon em polarizability of (8). An interpretation of this factor in terms of swelling leads to a $(6^{+11}_{-6})\%$ increase of the confinement radius. It has been predicted[4] that nuclear binding should lead to a quenching of the em polarizability due to Pauli blocking of the charged-pion photoproduction cross section. This effect has been calculated in the Fermi gas model, leading to a quenching of 17%. We may tentatively assume that this predicted[4] Pauli-blocking effect is the only medium correction which is relevant for the em polarizability measured by Compton scattering except for a possible swelling. Then the factor to be interpreted in terms of swelling would be $1.4^{+0.5}_{-0.3}$, corresponding to a $(12^{+12}_{-9})\%$ increase of the confinement radius.

In conclusion, we wish to state that Compton scattering has been proven to be a tool for a direct measurement of the bound-nucleon em polarizability. We do not claim that with this first experiment we have improved on the precision to which the polarizability of the bound nucleon is known. However, in view of the relatively short beam time of about 100 h available for this experiment before the shut down of the accelerator MAMI A, it appears quite likely that future developments will lead to a major improvement of the accuracy of the bound-nucleon electromagnetic polarizability as determined by nuclear Compton scattering.

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