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# Photon-induced proton knockout from $^{208}$Pb

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**Abstract**

Cross sections have been measured for the reaction $^{208}$Pb($\gamma$,p) leading to the low-lying ($\frac{1}{2}^+$, $\frac{3}{2}^+$) and ($\frac{11}{2}^-$, $\frac{5}{2}^+$) doublets and $\frac{7}{2}^+$ state in $^{207}$Tl using a high energy-resolution tagged photon beam of 41 to 57 MeV. The data are compared with results obtained with the reaction $^{208}$Pb(e,e$'$p) in the same recoil-momentum range. The recoil-momentum distributions derived from the ($\gamma$,p) data do not coincide with those obtained from the (e,e$'$p) data. Distorted-wave impulse-approximation (DWIA) calculations of which the input is constrained by the (e,e$'$p) data underestimate the ($\gamma$,p) data by typically one order of magnitude. An estimate of meson-exchange currents (MEC) effects using the Siegert theorem brings the DWIA-calculations close to the data. Random-phase approximation calculations also give a fair account of the data, but in this case MEC-effects are predicted to be less important.

The atomic nucleus is a many-body quantum system in which mesons are being exchanged between the constituent nucleons. Meson exchange gives rise to nucleon-nucleon correlations and allows the coupling of an external electromagnetic field to virtual mesons in the nucleus. In order to investigate the relative importance of nucleon-nucleon correlations and explicit meson-exchange currents in a heavy nucleus we performed complementary (e,e$'$p) and ($\gamma$,p) experiments on $^{208}$Pb. Recent results obtained with the reaction $^{208}$Pb(e,e$'$p) demonstrated the importance of long- and short-range correlations at high recoil momenta [1,2]. The $^{208}$Pb($\gamma$,p) experiment, which is reported in this paper, was expected to be sensitive to meson-exchange currents since the photon exclusively couples to currents in the nucleus. However, the mech-

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anism of the reaction ($\gamma$,p) is not as well understood as that of the reaction (e,e′p). While some authors [3,4] stress the role of the direct-knockout process, i.e. coupling to the nucleonic part of the current, others [5,6] found a large influence of meson-exchange currents.

Compared to previous ($\gamma$,p) studies, the present high energy-resolution $^{208}$Pb ($\gamma$,p) experiment has the advantage that it enables a comparison to the aforementioned results obtained with the reaction $^{208}$Pb(e,e′p) [1] in the same recoil-momentum range. It is thus possible to study the reaction ($\gamma$,p) under constraints set by the $^{208}$Pb(e,e′p) data. Furthermore, with $^{208}$Pb it is possible to study proton knockout from various quantum states (3s, 2d, 1g and 1h).

The experiment was carried out using the tagged photon beam of the MAX-Lab [7] at the University of Lund. The energy of the tagged-photon beam covered simultaneously the ranges from 41 to 48 MeV and 51 to 57 MeV with an energy resolution of about 230 keV. The tagging efficiency of the photon beam was on average 16%. The average total intensity of the tagged-photon beam was $3.7 \times 10^6$ photons/s. The target, placed at an angle of $19.8° \pm 0.5°$ with respect to the photon beam, consisted of a self-supporting 99% enriched $^{208}$Pb-foil with an average thickness of $24.5 \pm 0.2$ mg/cm$^2$. A box with mylar windows and filled with He-gas was placed around the target in order to reduce the background contribution due to ($\gamma$,p) events in air.

The knocked-out protons were detected in two solid-state detector telescopes developed by the nuclear physics group of the University of Edinburgh [8,9]. Each telescope consists of two Silicon Strip Detectors and a Hyperpure Germanium detector which measure the in-plane proton-emission angle and the energy of the proton, respectively. Together, the telescopes covered an angular range from 50° to 130° and subtended a solid angle of $413 \pm 20$ msr. The total systematic uncertainty in the cross sections is 9%.

As a check on the performance of the full experimental system, calibration runs were made on $^{12}$C at regular intervals during the experiment. Within the statistical and systematic uncertainty, the results of the $^{12}$C($\gamma$,p) runs reproduced the existing absolute cross sections for transitions to the ground state and first excited state in $^{11}$B [9–11].

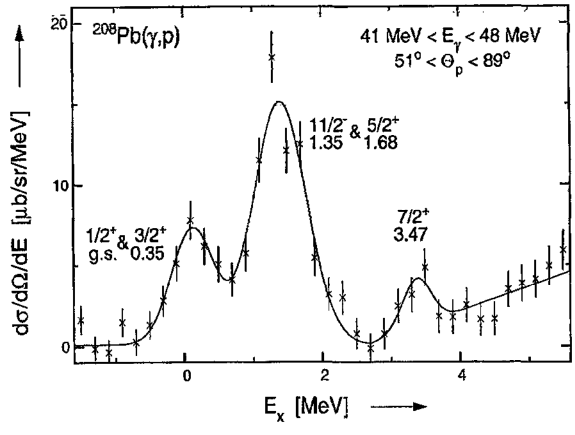


Fig. 1. Excitation-energy spectrum of the reaction $^{208}$Pb($\gamma$,p) showing the knockout of valence protons to discrete states in $^{207}$Tl, labelled by their spin, parity and excitation energy. The photon energy ranges from 41 to 48 MeV, and the proton-emission angle varies from 51° to 89°. The solid curve is the result of a fit to the spectrum involving Gaussian peak shapes and a linear continuum background starting at an excitation energy of 2.7 MeV.

In Fig. 1 a typical excitation-energy spectrum of the reaction $^{208}$Pb($\gamma$,p) is displayed. The spectrum represents integrated data accumulated in a photon-energy range from 41 to 48 MeV with proton-emission angles between 51° and 89°. Its shape is similar to spectra obtained with the reaction $^{208}$Pb(e,e′p) [1,12]. Both doublets and the transition to the $\frac{7}{2}^+$ state at an excitation energy of 3.47 MeV in $^{207}$Tl are clearly excited. The first doublet comprises transitions to the $\frac{1}{2}^+$ and $\frac{3}{2}^+$ states at excitation energies of 0.00 and 0.35 MeV, respectively. The second doublet has contributions from transitions to the $\frac{11}{2}^-$ and $\frac{5}{2}^+$ states in $^{207}$Tl at excitation energies of 1.35 and 1.68 MeV, respectively. The excitation-energy resolution is 470 keV.

Cross sections for both doublets and the $\frac{7}{2}^+$ state have been determined and are presented as a function of both the recoil momentum, $p_m$ (Fig. 2) and the proton-emission angle $\theta_p$ (Fig. 3). In plane-wave impulse-approximation (PWIA) the recoil (or missing) momentum, is identified as the initial momentum of the ejected proton. In order to obtain experimental recoil-momentum distributions we have plotted the data as a function of $p_m$ and divided the measured cross sections by an appropriate kinematical factor and a term representing the photon coupling to the transverse field generated by the proton magnetization

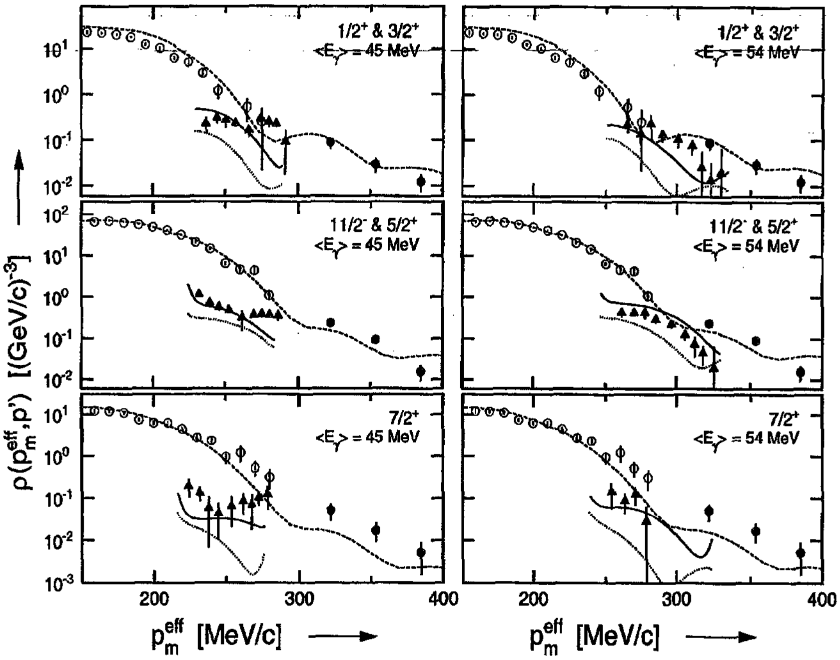


Fig. 2. Recoil-momentum distributions for transitions to the $(\frac{1}{2}^+, \frac{3}{2}^+)$ and $(\frac{11}{2}^-, \frac{5}{2}^+)$ doublets and the $\frac{7}{2}^+$ state in $^{207}$Tl. The present $^{208}$Pb($\gamma$,p) data, which have been taken at average photon energies of 45 and 54 MeV, are represented by solid triangles. The $^{208}$Pb(e,e′p) data are from Refs. [12] (open circles) and [1] (solid circles). The dashed curves are the result of (e,e′p) CDWIA-calculations including correlations as proposed by Mahaux and Sartor [16]. Similar DWIA-calculations for the reaction ($\gamma$,p) including these correlations are represented by the dotted curves. DWIA-calculations including an estimate of MEC-effects based on the Siegert theorem are given by the solid lines.

and convection current [13]. The representation of the data as recoil-momentum distributions enables the comparison of ($\gamma$,p) and (e,e′p) results on the same scale. In PWIA the recoil-momentum distributions obtained with either reaction should be identical, since they correspond to the squared Fourier transform of the radial overlap wave-function.

In Fig. 2 the recoil-momentum distributions for the transitions to the $(\frac{1}{2}^+, \frac{3}{2}^+)$ and $(\frac{11}{2}^-, \frac{5}{2}^+)$ doublets and the $\frac{7}{2}^+$ state in $^{207}$Tl as measured in the present $^{208}$Pb($\gamma$,p) experiment (solid triangles) are compared with those obtained with the reaction $^{208}$Pb(e,e′p) (open circles [12], solid circles [1]). In order to account for the kinematical dependence of electron distortions in the (e,e′p) measurements, the (e,e′p) data are plotted as a function of the effective missing momentum $p_m^{\rm eff}$ [1,14]. Since no electron distortions are present in the reaction ($\gamma$,p), $p_m^{\rm eff}$ reduces in this case to $p_m$.

The recoil-momentum distributions derived from the $^{208}$Pb($\gamma$,p) data do not coincide with those obtained from the $^{208}$Pb(e,e′p) data, i.e. no scaling of ($\gamma$,p) and (e,e′p) data is observed. Whereas the data for the first doublet are relatively close to the (e,e′p) data, larger discrepancies are observed for the second doublet and the $\frac{7}{2}^+$ state. Also, differences between the ($\gamma$,p) data obtained at high and low photon energy are visible. The absence of scaling is in contrast to observations made on low-mass nuclei where scaling appears to occur [3]. However, a recently performed comparison of existing (e,e′p) and ($\gamma$,p) data on various nuclei taken at $E_\gamma$ = 60 MeV [13] also concluded that no general scaling could be observed. The present data confirm this conclusion, although the scale-breaking effects seem to be larger than previously reported, especially at $E_\gamma$ = 45 MeV.

The dashed curves in Fig. 2 represent (e,e′p) distorted-wave impulse-approximation (CDWIA) calculations [15] including electron and proton distortions, and nucleon-nucleon (NN) correlations. Details are given in Ref. [1]. At high $p_m^{\mathrm{eff}}$ the inclusion of long-range NN-correlations in a quasi-particle approach [16], is crucial for a proper description of the data.

Employing the quasi-particle wave functions and normalisation factors as obtained from $^{208}$Pb(e,e′p) [1], we performed ($\gamma$,p) distorted-wave impulse-approximation (DWIA) calculations [4,13] including proton distortions, which are represented by the dotted curves in Fig. 2. Hence, these ($\gamma$,p) cross sections have been calculated in the same framework as was used for the $^{208}$Pb(e,e′p) calculations, which is based on the direct-knockout mechanism. The optical-model parameters used in the ($\gamma$,p) calculations have been taken from Ref. [17]. Applying an alternative parameterisation [18] the sensitivity of the calculations to the optical-model parameters is estimated to be 15%. However, this estimate does not include possible contributions from channel-couplings in the final state, as they are not included in DWIA-calculations. Since the photon-energy range, $E_\gamma$, is quite large, and thus also the range of outgoing proton energies, $T_p$, separate calculations have been performed for six different ($E_\gamma$,$T_p$)-combinations. The final curves result from weighing the individual calculations with the experimentally observed fraction of the total photon flux.

The ($\gamma$,p) DWIA-calculations are far below those of (e,e′p), which is mainly due to the increase of final-state interaction effects in the ($\gamma$,p) calculations. Whereas $T_p$ is 100 MeV in the $^{208}$Pb(e,e′p) experiment, it is only 30–40 MeV at low $E_\gamma$ and 40–50 MeV at high $E_\gamma$ in the $^{208}$Pb($\gamma$,p) experiment. For all transitions the ($\gamma$,p) DWIA-calculations underestimate the data by typically one order of magnitude.

In previous comparisons between ($\gamma$,p) cross sections and DWIA-calculations the effects of long-range NN-correlations were not considered, see Ref. [13], for instance. However, these effects are essential for a good description of the $^{208}$Pb(e,e′p) data taken at high $p_m$, i.e. $p_m \geq 300$ MeV/c. Therefore, the effects of long-range correlations have also been included in the ($\gamma$,p) DWIA-calculations. As the ($\gamma$,p) data cover somewhat smaller missing momenta than the (e,e′p) data, the effects of long-range NN-correlations are also smaller, i.e. only a factor of 2 or less. Hence, the measured data cannot be described within a DWIA framework with or without the inclusion of NN-correlations.

Meson-exchange currents (MEC) are possibly at the origin of the discrepancy between the DWIA-calculations and the data. An estimate of the effects of meson-exchange can be obtained by applying the Siegert theorem [19]. This method [13,20] involves the multiplication of the (pure) DWIA-calculations with the ratio of PWIA cross sections with and without application of the Siegert theorem. The Siegert theorem, which is based on current conservation, effectively accounts for nuclear currents not included in the direct-knockout framework. We note that this type of calculation has the advantage that the constraints derived from the (e,e′p) data can be kept. As shown in Fig. 2 by the solid curves, the resulting calculations give a fair account of the data. Hence, within the limitations of the 'DWIA+Siegert' framework, MEC-effects seem to dominate the reaction $^{208}$Pb($\gamma$,p). It should be kept in mind, however, that the Siegert approach is exact only in the limit of small photon momenta. Away from this limit, possible contributions of two-body currents are neglected.

It is desirable to incorporate nucleonic currents, MEC-effects, NN-correlations and final-state interactions in one self-consistent framework. This has been done by Ryckebusch et al. [6,21], who have performed coupled-channel calculations in the random-phase approximation (RPA). In this model the nuclear wave functions are generated with the effective Skyrme NN-interaction [22], including the coupling to the collective properties of the target and recoil nucleus, multi-step processes and rescattering effects. The MEC-effects are introduced as photon absorption on two-body currents by a minimal substitution in the Skyrme effective NN-Hamiltonian, preserving gauge invariance. Despite the inclusion of multi-step processes and rescattering effects, the final-state interaction is known to be incompletely treated in the RPA-framework as only 1p1h-configurations are considered. The results of these RPA-plus-MEC calculations are represented by the solid curves in Fig. 3 in which the same $^{208}$Pb($\gamma$,p) data as already displayed in Fig. 2 are shown as angular distributions. Note, that all calculations in this figure have been normalised and averaged in the same manner as was previously described in relation to Fig. 2. Except for the second doublet, the RPA-plus-MEC calculations describe the data fairly well.

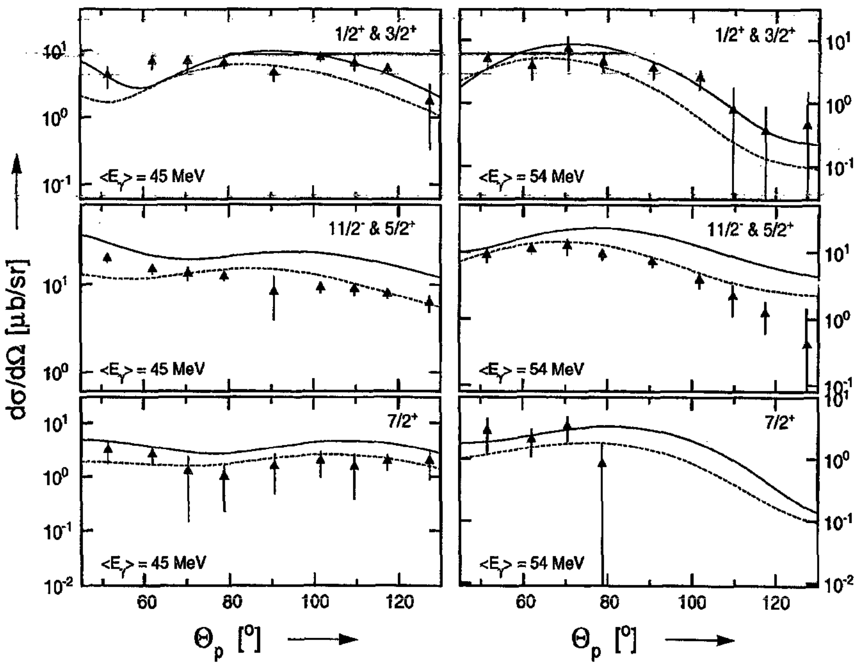


Fig. 3. Angular distributions for transitions to the ($\frac{1}{2}^+$, $\frac{3}{2}^+$) and ($\frac{11}{2}^-$, $\frac{5}{2}^+$) doublets and the $\frac{7}{2}^+$ state in $^{207}$Tl at average photon energies of 45 and 54 MeV. RPA calculations with and without MEC-effects are given by the solid and dashed lines, respectively.

In order to investigate the relative importance of MEC-effects in the RPA-framework, calculations were performed in which the photon only couples to the nucleon current (impulse approximation). The resulting calculations (dashed curves in Fig. 3) show that the exclusion of MEC-effects reduces the calculated cross sections by a factor of two on average. Hence, the effects of MEC are relatively less important in the RPA-framework as compared to the 'DWIA+Siegert' estimate. Note, that a larger contribution of MEC-effects within the RPA-framework was observed for low-mass nuclei [21].

In summary, a photon-induced proton knockout experiment on $^{208}$Pb has been carried out covering proton-emission angles from 50° to 130° and using photon energies ranging from 41 to 58 MeV. Data for transitions to the ($\frac{1}{2}^+$, $\frac{3}{2}^+$) and ($\frac{11}{2}^-$, $\frac{5}{2}^+$) doublets and the $\frac{7}{2}^+$ state in $^{207}$Tl have been compared with results obtained with the reaction $^{208}$Pb(e,e′p) at the same recoil momenta. The recoil-momentum distributions derived from the ($\gamma$,p) data do not coincide with those obtained from the (e,e′p) data. DWIA-calculations that are constrained by the $^{208}$Pb(e,e′p) results underestimate the data by an order of magnitude. An estimate of MEC-effects using the Siegert theorem brings the DWIA-calculations close to the data. RPA-calculations also give a fair account of the data, but in this case MEC-effects are predicted to be of relatively less importance. Since both frameworks have their restrictions, more detailed calculations are called for in order to obtain a proper understanding of the reaction $^{208}$Pb($\gamma$,p). Such calculations should be constrained by the presently available ($\gamma$,p) and (e,e′p) data.

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