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Polarization Effects in a Dirac Equation Approach to Photonuclear Reactions

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Résumé – Nous avons calculé, utilisant la phénoménologie de Dirac, l'amplitude de réactions photonucléaires correspondant au diagramme de premier ordre. Le mouvement du nucleon est décrit à l'aide de l'équation de Dirac, et les effets de distorsion sont pris en considération. Les calculs sont effectués pour les observables de polarisation, et nous comparons avec l'expérience.

Abstract – The amplitude corresponding to the lowest order diagram for photonuclear reactions is calculated in the framework of Dirac phenomenology. The nucleon motion is described using the Dirac equation and distortion effects are taken into account. Calculations are carried out for the polarization observables in the reaction and some comparison with experiment is discussed.

The relativistic approach to nuclear dynamics has been successful in accounting for the observed properties of nuclear matter and finite nuclei /1/. It also gives a description of polarization observables in nucleon elastic and inelastic scattering which is superior to that obtained using the traditional non-relativistic approach. This success encourages further investigation of other reactions in the same framework with the objective of testing the range of validity of this approach and to assess whether outstanding difficulties in these reactions can be resolved by relying on relativistic dynamics.

Photonuclear reactions at intermediate energies are good candidates for such investigations. There have been a number of recent measurements of the angular distribution for the (γ,p) reaction on 16O which seem to be difficult to reconcile with the existing non-relativistic calculations. Moreover, such reactions induced by intermediate energy photons or nucleons do involve large momentum transfer. Under these circumstances the lower components of the Dirac wavefunctions are not small compared to the upper components, and hence relativistic effects may be important.

There are several mechanisms that can contribute to a photonuclear reaction. The basic and simplest among them is the direct knockout mechanism in which the photon interacts with a single nucleon which is ejected, leaving the residual nucleus in a discrete final state. The present paper outlines the calculation of the amplitude for this process and discusses some aspects of the polarization effects associated with this mechanism.

The amplitude is calculated in a relativistic distorted wave Born approximation /2,3/. For a (γ,p) reaction on a nucleus with spin J_i and assuming the bound proton is in a pure single particle state, the amplitude is written as:

\[ T_{J_f J_p}^{M_f M_p} = (J_f J_p ; M_f M_p | J_i J_i) \int |\psi_{s_f}^{(-)}(x)H_{em}^{*}(x)|\psi_{M_f}(x)\,d^3x \]  

(1)

In the above equation the final state of the ejected proton is described by the spinor \(\psi_{s_f}^{(-)}(x)\) where \(s_f\) refers to the spin projection, and the bound state is represented by the spinor \(\psi_{M_f}(x)\) with angular momentum \(J_p\) and projection \(M_p\). The interaction of the photon with the nucleon is given by the Hamiltonian \(H_{em}^{\xi}(x)\):

\[ H_{em}^{\xi}(x) = \frac{2}{\sqrt{2}} A_{\mu}(x) + \frac{\sigma_{\mu\nu}F_{\mu\nu}(x)}{2} \]

where \(A_{\mu}(x)\) is the four-vector potential of the incident photon with polarization \(\xi\), and \(F_{\mu\nu}(x)\) is the corresponding

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electromagnetic field tensor. The charge number of the nucleon is denoted by $Z_N$ and its anomalous magnetic moment by $\kappa_N \mu_N$.

The nucleon bound state wavefunction can be calculated using the Dirac-Hartree approximation. These calculations attribute the large scalar and vector binding potential to the exchange of $\sigma$ and $\omega$ mesons, respectively, and are found to give reasonably good results for the binding energy and spin-orbit splitting in nuclei. Corrections due to vacuum polarization have been added in the one-baryon-loop approximation by Horowitz and Serot. An alternate approach is to use a phenomenological Woods-Saxon binding potential whose parameters are chosen such that the single-particle binding energies are reproduced.

The continuum wavefunction is a distorted wave determined from analyzing the appropriate elastic scattering data of the nucleon-nucleus system. In this case the Dirac potentials are complex. These can be determined from microscopic models such as the relativistic impulse approximation or from folding model calculations. Phenomenological analyses, in which the potentials are parameterized in terms of Woods-Saxon or similar functions, have also been carried out extensively.

The present approach is found to give reasonable agreement with the observed cross sections in the intermediate energy range, particularly at forward angles. There remain differences between the calculations and the observed data. These are attributed to other mechanisms such as meson exchange currents and $\Delta$-isobar contributions, as well as to uncertainties in the determination of the Dirac wavefunctions.

A further test of the model will be through the comparison of its predictions with the polarization and analyzing power data. There is a scarcity of data on the polarization effects in photonuclear reactions, particularly at intermediate energies. Our calculations for polarization in $(\gamma, p')$ reactions (and for the analyzing power in the inverse $(p, \gamma)$ reactions) show that the results are sensitive to the type of bound state wavefunctions used in the calculations. The sensitivity is not as pronounced at lower energies. Lower energies and very light nuclei are not the best candidates for testing the present model, yet this is where the measurements have been performed in the past. With this in mind we show below some of the comparisons of our calculations with existing data.

Figs. 1 and 2 show the results for the reaction $^{15}\text{N}(p', \gamma)^{16}\text{O}$ at 49.7 MeV for the ground and second excited states. The solid (dashed) line corresponds to a Dirac-Hartree (Dirac-Hartree plus vacuum polarization corrections) bound state wavefunction. The $p_{1/2}$ proton in the $^{16}\text{O}$ ground state is underbound by 2.9 MeV by the Hartree potential and by 1.2 MeV by the Hartree potential with vacuum polarization corrections; this is a general feature of these calculations. For the second excited state the binding scalar potential was adjusted in order to reproduce the empirical binding energy, otherwise the $d_{5/2}$ proton would barely be bound by the Hartree potential and would be unbound with the vacuum polarization-corrected Hartree potential.

The optical potentials are derived...
from $p + ^{16}O$ elastic cross section data at 50 MeV. The qualitative features of the data are reproduced.

Fig. 3 shows a similar comparison for the $^{12}C(p,\gamma)^{13}N$(g.s.) data at 40 MeV /12/. The data here extend over a much wider angular range and are better reproduced by our calculations. In this case the bound state wavefunction is obtained from the Dirac-Hartree calculations and the distorting potential from elastic $\vec{p} + ^{12}C$ scattering at 50 MeV. The captured proton in this case is overbound by 0.5 MeV.

Calculations were also performed for the reaction $^3H(\vec{p},\gamma)^4He$ at 300 MeV /13/. The distorting potentials were taken from an analysis of $\vec{p} + ^3He$ scattering at this energy /14/. The Dirac-Hartree model could not be used to generate the bound state wavefunction in this case. Instead a phenomenological potential is used. Because of the sensitivity of the results to the bound state in this energy region, several different wavefunctions with the same binding energy were obtained. Some give close agreement with the analyzing power data. We attempted to put a further constraint on these functions by performing a comparison with a parameterized form of the charge form factor of $^4He$ from which the meson exchange current effects have been subtracted /15/. The results shown in Fig. 4 are obtained from a wavefunction that gives reasonable agreement with this parameterized charge form factor. Note that the agreement is reasonable with the analyzing power.

In conclusion, we believe the above comparisons indicate that the present calculations are a reasonable way of accounting for the single nucleon knockout contribution to the photonuclear process, one on which to build a calculational approach to the higher order processes. It is our hope that more experimental data on polarization effects in these reactions will become available in the near future.

![Fig. 3: Analyzing power for the $^{12}C(p,\gamma)^{13}N$ reaction at 40 MeV /12/. The curve corresponds to a Dirac-Hartree bound state wavefunction.](image1)

![Fig. 4: Analyzing power for the $^3H(p,\gamma)^4He$ reaction at 300 MeV /13/. The curve corresponds to a bound state wavefunction generated with a Woods-Saxon potential (see text for details).](image2)

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