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Calculation of two-step processes in the (e,e′p) reaction

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It is shown that coupled-channels effects in the (e,e′p) reaction can be calculated to a good approximation with existing programs for pickup reactions. Some examples of two-step processes in the (e,e′p) reaction are given.

Since the electromagnetic interaction is well known and relatively weak, the (e,e′p) reaction is an excellent tool to study single-particle properties of nuclei.[1] In order to fully exploit this potential, one has to be sure that the final-state interaction (FSI) between the outgoing proton and the residual nucleus is well under control. This FSI is usually described via an optical-model potential. It is then of interest that one is able to estimate the effect of possible two-step excitations in the outgoing channel. This is important, for instance, if weak transitions are studied with the aim of determining small components of wave functions. In such a study[2] for the reaction ^{12}C(e,e′p)^{11}B it turned out that the cross section for the transition to the $\frac{5}{2}^-$ state in ^{11}B, which could result from knockout followed by inelastic excitation, was rather small,[3] in contrast to the situation in the (p,2p) reaction. Another example is the recent measurement of the ratio of longitudinal to transverse response functions in (e,e′p). The measured ratio differs from the one predicted by the impulse approximation.[4] This has raised the question if the charge-exchange process (e,e′n)(n,p) could contribute to the observed effect.[5]

For these reasons one would like to be able to estimate the importance of two-step processes in the (e,e′p) reaction. Unfortunately the existing codes for calculating (e,e′p) cross sections cannot handle coupled channels in the final state. We demonstrate in this Communication that to a rather good approximation the (e,e′p) reaction can be treated as a pick-up reaction, so that existing codes for calculating two-step processes in the latter can also be used for (e,e′p).

In the distorted-wave impulse approximation (DWIA) the cross section for (e,e′p) is usually written in the following form:[1]

$$\frac{d^6\sigma}{d\mathbf{e}'d\mathbf{p}'}=k\sigma_{ep}S^D(E_m,\mathbf{p}_m,\mathbf{p}') \ , \tag{1}$$

where σ_{ep} is the free electron-proton cross section and S^D is the (distorted) spectral function, which depends on the missing energy E_m, the missing momentum $\mathbf{p}_m$, and—due to the FSI—also on the momentum $\mathbf{p}'$ of the outgoing proton [the electrons are described by plane waves in Eq. (1)]. The factorization in (1) is an approximation, which is nearly exact in parallel kinematics and correct to within 10–15% in other cases.[6]

For a transition to a discrete final state the spectral function can be written as $S^D=\rho^D(\mathbf{p}_m,\mathbf{p}')\delta(E-E_m)$, where the (distorted) momentum distribution ρ^D is given by[1]

$$\rho^D(\mathbf{p}_m,\mathbf{p}')=\left|\frac{1}{(2\pi)^3}\int \chi^{(-)*}(\mathbf{r}) \times\exp\left(i\frac{A-1}{A}\mathbf{q}\cdot\mathbf{r}\right)\phi_\alpha(\mathbf{r})d\mathbf{r}\right|^2 . \tag{2}$$

The exponential results from the (plane) incoming and outgoing electron waves, ϕ_α is the bound state wave function of the proton, and χ is the continuum wave function of the outgoing proton, as given, for instance, by an optical model. However, formula (2) can also be viewed as the zero-range T-matrix element for a pick-up reaction, in which a "particle" described by the plane wave factor $\exp[i(A-1)/A\mathbf{q}\cdot\mathbf{r}]$ picks up a proton from orbit α, while the outgoing particle (again a proton) is described by the distorted wave χ. The mass and energy of the incoming "particle" and the Q value of the reaction should be chosen in such a way that the kinematics of the reaction, i.e., the values of $\mathbf{q}$ and $\mathbf{p}'$, are the same as in the (e,e′p) reaction. This analogy is illustrated in Fig. 1.

The equivalence between the factorized description of the (e,e′p) reaction and a pick-up reaction was checked by calculating the knockout of a $1p_{3/2}$ proton from ^{12}C and of a $3s_{1/2}$ proton from ^{208}Pb with both the (e,e′p) program PEEP[7] and the pick-up program DWUCK.[8] The results agreed quantitatively.

Two-step processes can now easily be calculated by taking for the distorted wave χ in (2), a coupled-channels wave function, as is done, for instance, implicitly in a program like CHUCK.[8] We will present two examples.

The first is the excitation of the $\frac{5}{2}^-$ and $\frac{7}{2}^-$ core-excited states at E_x=4.445 and 6.743 MeV, respectively, in the

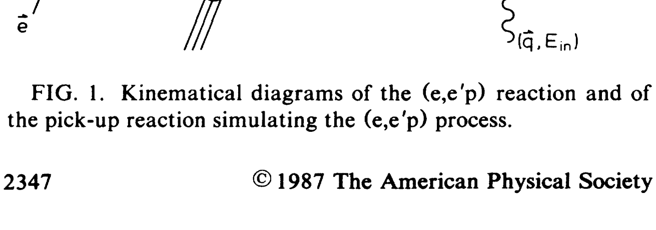

FIG. 1. Kinematical diagrams of the (e,e′p) reaction and of the pick-up reaction simulating the (e,e′p) process.

^{12}C(e,e'p)^{11}B reaction. Assuming empty $1f$ orbits in the ^{12}C ground state, these transitions are forbidden in a one-step reaction. The experimental data at $T_p=70$ MeV yielded an upper limit for the momentum density of the $\frac{5}{2}^-$ state of 4×10^{-11} (MeV/c)$^{-3}$ (Ref. 9) to be compared with typically 1×10^{-9} (MeV/c)$^{-3}$ for a weak transition.[3] The two-step excitation of the $\frac{5}{2}^-$ and the $\frac{7}{2}^-$ state via knockout of a $1p_{3/2}$ proton leading to the ground state of ^{11}B followed by an $\lambda=2$ inelastic excitation was calculated using the program CHUCK. Optical-model parameters from Ref. 10 were used, while the β values for the inelastic excitation were taken from Ref. 11. The results, represented as a momentum distribution, are shown in Fig. 2. Indeed, the calculated momentum distribution for the $\frac{5}{2}^-$ state is smaller than the measured upper limit. The calculations also indicate that the two-step excitation of the $\frac{7}{2}^-$ state, which could not be separated experimentally from the $\frac{1}{2}^+$ state at 6.793 MeV[2], is also very small. It is interesting to note that the "momentum distribution" for the $\frac{5}{2}^-$ and the $\frac{7}{2}^-$ states depends strongly on the kinematics, see Fig. 2. This is in contrast to the case of direct knockout, the reason being that the latter depends mainly on the value of p_m only, whereas the two-step process also depends on the angle θ between $\mathbf{q}$ and $\mathbf{p}_m$.

The second example is the influence of charge exchange on the transverse part of the reaction ^{12}C(e,e'p)^{11}B$_{gs}$ at $T_p=70$ MeV. This is of interest because discrepancies have been observed in the ratio of longitudinal to transverse response functions, which might be (partly) due to charge-exchange processes.[4] Both the (e,e'p) and the (e,e'n)(n,p) process were calculated with CHUCK and combined coherently. The charge exchange was calculated using a Lane potential, taken, as well as the diagonal potentials, from the isospin-dependent potential of Ref. 12. We find essentially the same results as obtained from calculations, in which the Lane equations for the final state were diagonalized,[5] i.e., an enhancement of the transverse part of the cross section of about 2% relative to the longitudinal part, which is about 30% of the observed effect.

In conclusion, we found a simple way to simulate the (e,e'p) reaction by a pick-up reaction, so that two-step processes in the former can be calculated with existing programs for the latter. Essentially the only approximation involved is the factorization of the (e,e'p) cross section in an electron-nucleon part and a nuclear part, which is known to be rather good. The method can be used to calculate all kinds of coupled-channels effects, e.g., the contribution of sequential pick-up processes in the (e,e,'d) reaction.

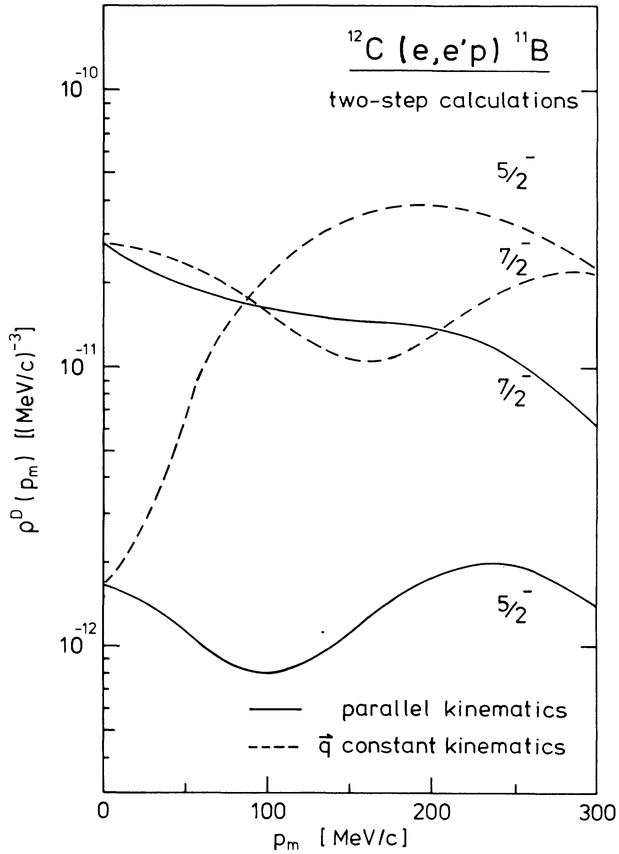

FIG. 2. Calculated momentum distributions for the two-step excitation of the $\frac{5}{2}^-$ and $\frac{7}{2}^-$ states in ^{11}B in the ^{12}C(e,e'p) reaction. In parallel kinematics ($\mathbf{p}\|\mathbf{q}$) q varies, while $\theta=0$ (see Fig. 1 for the definition of θ). In q-constant kinematics θ varies. The measured upper limit in parallel kinematics for the $\frac{5}{2}^-$ state is 4×10^{-11} (MeV/c)$^{-3}$.

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