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Angular correlations and missing energy spectrum in quasifree electron scattering

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The angular correlations and missing energy spectrum in quasifree electron scattering are studied in the unfactorized distorted wave impulse approximation. The present approach, in the nonrelativistic description, effectively includes the finer aspects of the process, namely the off-energy-shell effect and the spin-orbit coupling, which are neglected or approximated in the usual factorization methods. A comparative study between the factorized and unfactorized methods reveals that the unfactorized cross section not only accounts for the absolute value but also a possible asymmetry in its distribution. The study of the off-shell influence on spherical and nonspherical nuclei indicates that the off-shell effect is to increase with the increase of nuclear deformation.

I. INTRODUCTION

The quasifree knockout reactions[1-3] are exploited to determine unique and useful information pertaining to the single particle momentum distributions, separation energies, and nucleon clusters. The usual method[3-5] of factorizing the electron-nucleus cross section into the electron-proton free cross section (Rosenbluth cross section) and the nuclear structure part neglects the spin-orbit and off-energy-shell effects which, however, cannot be avoided in nuclear problems. The approach is also unable to reproduce the experimental value of the cross section. It has been shown[3,4] that the factorized cross section, which is proportional to the spectral density function, is acceptable only to within $\sim 10\%$. The importance of the unfactorized cross section in the distorted wave impulse approximation (DWIA) has been stressed in the relativistic Feynman description, but such calculations[4] do not include the off-shell character in a realistic way, except for the use of an effective mass of the bound initial particle. Moreover, the inclusion of the spin-orbit term in the final state interaction leads to insurmountable difficulties in the relativistic procedure. The aim of the present paper is to show the validity and the necessity of the unfactorized DWIA approach in the nonrelativistic description. This method seems to be more realistic since it effectively takes care of the finer aspects of the scattering process, namely, the off-energy-shell effect and the spin-orbit coupling in the final state interaction, which are gaining importance in the recent studies of this subject matter.[6] In this study, we present the influence of these aspects on the unfactorized angular correlations and missing energy spectrum. In an earlier paper,[7] we have presented our investigation on the off-shell and nuclear structure effects on the coincidence cross section of ^{12}C. Since the electromagnetic interaction plays an important role in (e,e′p) reactions, the method of evaluating the electron-nucleon scattering amplitude becomes quite significant. A consistent nonrelativistic computation of the (e,e′p) cross section is carried out making use of the off-shell scattering amplitude. The off-shell effect is simulated by the gradient operator[7,8] $\vec{\nabla}$ in order to take into account the variation of the nucleon momentum through the nuclear medium and it is incorporated in the evaluation of the unfactorized scattering amplitude. With a view to study the influence of this effect on nuclear deformation, we present the angular correlations for both spherical and nonspherical nuclei. The off-shell influence is found to be more predominant in nonspherical nuclei than the spherical one. The effect is also found to reduce the cross sections for various orbital levels of the knockout nucleon over a wide range of recoil momentum. The reduction factor,[3] which is the ratio of the distorted to the plane wave cross sections, is found to increase not only with the increase of orbital levels of the knockout nucleon, but also with the nuclear deformation leading to nonspherical shapes, yielding a maximum reduction factor[9] of 0.72 for ^{12}C. The inclusion of the off-shell effect in the unfactorized distorted wave calculation reduces the reduction factor for the various orbital levels and the results are in better agreement with the experimental values.[3]

A comparative study of the factorized and unfactorized DWIA angular correlations is carried out. The validity of the unfactorized approach is justified, since it not only accounts for the absolute value but also for a possible asymmetry in the experimental cross section.

The missing energy spectrum of the quasifree scattering is studied using the unfactorized DWIA method in the nonrelativistic description. The results indicate that the peaks of the spectrum are much influenced by the finer aspects of the approach. The relative importance of the real and imaginary components of the spin-orbit term in the final state interaction is also studied by expanding the outgoing proton wave functions in terms of the definite final angular momentum states.[10,11] It is found that the cross sections around the peaks are much affected by these components in the various choices of optical potentials.

II. ANGULAR CORRELATIONS

The calculation of (e,e′p) angular correlations requires the computation of the off-shell scattering amplitude which can be done by two different methods. The relativistic Feynman technique with one photon exchange between the incident electron and the knockout nucleon is used in one method, and in the other the electron-nucleon interaction is reduced to a nonrelativistic form by means of Foldy-Wouthuysen transformation. The transformed Hamiltonian is then expanded in a power series of the nucleon recoil velocity and the series was truncated at second order by McVoy and Van Hove.[12] In the first approach, the initial nucleon is described by a free Dirac spinor and its off-shell character is not taken into account. The electromagnetic vertex of the nucleon is described by an on-shell form factor and the off-shell behavior of the scattering amplitude is simply extrapolated. A comparative study of different off-shell extrapolations of the Rosenbluth cross section and the relative ambiguities involved are elaborated elsewhere.[13] In order to take into account the off-energy-shell effect and the spin-orbit interaction precisely, we follow the nonrelativistic method of computing the (e,e′p) cross section, which has already been developed by one of us in the plane wave impulse approximation.[2]

Furthermore, in the nonrelativistic description itself the cross section can be evaluated either in the factorized or in the unfactorized form. In the usual factorization procedure, the cross section is given by

$$\frac{d^3\sigma}{dE_f d\Omega_e d\Omega_p}=K\left[\frac{d\sigma}{d\Omega_e}\right]_{ep} S(E,P)\,, \tag{1}$$

where K is a kinematical factor depending only on the energies of the incoming and outgoing electron, $(d\sigma/d\Omega_e)_{ep}$ is the free electron-proton cross section, and $S(E,P)$ is the spectral density function. When the proton is free and at rest, one can easily calculate the electron-proton cross section from the electric and magnetic form factors. But the result is a rapidly varying function of the kinematical variables and it will be quite different for a moving bound proton. Moreover, it holds only for on-shell kinematics and is not valid for the off-shell situation. However, the off-shell behavior of the cross section can be extrapolated in this procedure,[4] but it will have its own limitation and ambiguity. The inclusion of the spin-orbit distortion, which is an important aspect in the final state interaction, becomes impossible in the factorization procedure.[10] The presence of spin-orbit coupling demands an unfactorized approach, wherein the spectral function turns to be nondiagonal and the computation becomes extremely difficult. Also, the factorization method does not account for the absolute value of the cross section and a possible asymmetry in its distribution. On the contrary, the cross section can be calculated in a straightforward way, making use of the nonrelativistic off-shell scattering amplitude in the unfactorized approach, in which all the finer details of the process are precisely accounted for.

The scattering amplitude for the process with the Hamiltonian of McVoy and Van Hove is given by

$$M=-\left[\frac{4\pi e^2}{q_\mu^2}\right]\langle u_f\,|\,Q-\vec{\alpha}\cdot\vec{J}\,|\,u_i\rangle F(q_\mu^2)$$
$$\times\delta\left[E_i-E_f-E_s-\frac{p_f^2}{2M}-\frac{q_R^2}{2(A-1)M}\right]. \tag{2}$$

Unlike the earlier calculations,[14,15] the off-shell effect is exactly incorporated in the calculation through the gradient operator $\vec{\nabla}$, which effectively replaces the nucleon momentum $\vec{p}$ contained in the term $\vec{\alpha}\cdot\vec{J}$. But for the extrapolation of the off-shell character, the factorization procedures[4,10] do not include this effect properly. Using the angular momentum algebra, a compact form for the amplitude is given by

$$J=\left[\frac{1}{2M}\right]\langle \vec{p}_f,\tfrac{1}{2}m_s\,|\,e^{i\vec{q}\cdot\vec{r}}\sum_{n,N=0,1}\sum_{\mu\lambda\nu}\sigma_N^\lambda\nabla_n^\mu \vec{A}_{nN}(\mu\lambda\nu)K_N^\nu\,|\,u_{nLJ}(r),L\tfrac{1}{2}JM\rangle\,. \tag{3}$$

The notations and symbols are defined in our earlier work.[7] The significance of this simple form is that once it is calculated the remaining terms of the matrix element can easily be computed by choosing the momentum transfer $\vec{q}$ along Z direction.

The spin-orbit distortion is effectively introduced in the evaluation of the scattering amplitude by taking their coupling in the final state.

$$|\,\vec{p}_f,\tfrac{1}{2}m_s\rangle=|\,e^{i\vec{p}_f\cdot\vec{r}},\tfrac{1}{2}m_s\rangle=\sum_{l_f m_f}4\pi i^{l_f}j_{l_f}(p_f r)Y_{l_f}^{m_f}(\hat{r})Y_{l_f}^{*m_f}(\hat{p}_f)\chi_{(1/2)m_s}\,, \tag{4}$$

$$=\sum_{l_f m_f J_f}4\pi i^{l_f}g_{l_f J_f}(p_f r)Y_{l_f}^{*m_f}(\hat{p}_f)C(l_f\tfrac{1}{2}J_f,m_f m_s M_f)\,|\,l_f\tfrac{1}{2}J_f M_f\rangle\,. \tag{5}$$

The radial part of the proton wave function $g_{l_f j_f}(p_f r)$ is obtained by solving the Schrödinger wave equation with various choices of optical potentials, including the spin-orbit components.

The angular correlations are obtained for the nuclei ^{12}C, ^{28}Si, and ^{40}Ca by varying the proton angle and fixing the angle of the electron and the proton kinetic energy.

III. MISSING ENERGY SPECTRUM

In the quasifree scattering, when a nucleon is ejected from a nucleus by probe particles, energy and momentum conservation require that

$$E_s=E_i-E_f-E_p-\frac{q_R^2}{2(A-1)M}\,, \tag{6}$$

$$\vec{q}_R = -\vec{p}_i = \vec{k}_i - \vec{k}_f - \vec{p}_f \ , \tag{7}$$

where $\vec{k}_i$ and $\vec{k}_f$ ($\vec{p}_i$ and $\vec{p}_f$) are the initial and final momentum of the electron (proton). E_i and E_f represent the initial and final energies of the electron and E_p denotes the final proton energy. E_s is the separation energy required to knock out the proton leaving the residual nucleus in the excited state with momentum $\vec{q}_R$. A peak in the spectrum of the number of electron-proton coincidences as a function of the missing energy,[16] given by

$$E_M = E_i - E_f - E_p \ , \tag{8}$$

reveals the existence of a bound state of the nucleon, the separating energy of which is simply $E_s = E_M$ in the limit of the recoil energy tending to zero. The residual nucleus is left in an incoherent superposition of highly excited states which have a natural width Γ due to their finite lifetime.[17,18]

The cross section for the (e,e′p) process in the coplanar case is given by[19]

$$\frac{d^4\sigma}{dE_f d\Omega_e dE_p d\Omega_p} = K(\langle u_f \,|\, Q - \vec{\alpha}\cdot\vec{J} \,|\, u_i \rangle)^2 \times \delta\left[E_i - E_f - \frac{p_f^2}{2M} - \frac{q_R^2}{2(A-1)M} - E_s\right] , \tag{9}$$

where

$$K = \left[\frac{4\pi e^2}{q_\mu^2}\right]^2 |F(q_\mu^2)|^2 \frac{\pi}{2E_i} \frac{k_f p_f E_p}{(2\pi)^6} \ . \tag{10}$$

The quantities involved in these equations are defined in earlier works.[2,7] The above expression gives the cross section for a transition from the ground state of the nucleus to a particular state of the residual nucleus. Experimentally the energy spectra can be measured by varying E_s in different ways; for instance, varying E_i for fixed E_f and E_p values. However, the energy spectra cannot be calculated unless the delta function is replaced. Also, the extraction of a nucleon from a nucleus leads to a large number of final excited states because of the different possible couplings between the spin and isospin of the resulting hole and the remainder of the nucleus. In order to account for the finite widths γ_f of the final levels and the energy resolution on $E_s, \Delta E_s$, we replace the energy conservation delta function by the Gaussian[18]

$$\frac{1}{\sigma_f}\left[\frac{2}{\pi}\right]^{1/2} e^{-2\frac{(E_M - E_s)^2}{\sigma_f^2}}$$

with a full width at half maximum

$$\Gamma = (E_s^2 + \gamma_f^2)^{1/2} = 1.18\sigma_f \ . \tag{11}$$

Thus the cross section corresponding to the excitation of the fth level of the residual nucleus becomes

$$\frac{d^4\sigma}{dE_f d\Omega_e dE_p d\Omega_p} = K(\langle u_f \,|\, Q - \vec{\alpha}\cdot\vec{J} \,|\, u_i \rangle)^2 \frac{1}{\sigma_f}\left[\frac{2}{\pi}\right]^{1/2} \times e^{-2\frac{(E_M - E_s)^2}{\sigma_f^2}} \ . \tag{12}$$

The above expression allows one to directly compare the theoretical calculations on energy spectra with experimental results. The matrix element in the expression is calculated in the unfactorized DWIA, wherein the off-energy-shell effects are exactly incorporated through the gradient operator $\vec{\nabla}$. The results are compared with earlier work[19] which does not include all the terms in the matrix element, and the spin-orbit interaction besides the off-shell effect.

IV. RESULTS AND DISCUSSION

The angular correlations have been calculated numerically for the various orbital levels of the knockout nucleons in ^{40}Ca, ^{28}Si, and ^{12}C. These correlations are obtained by varying the proton angle and fixing the angle of the scattered electron at 52.9°, and the outgoing proton energy at 87 MeV. The potential parameters of Elton and Swift[20] (ES), which correctly predict the separation energy of the protons in different shells, are used to develop the bound state wave functions. For the final state interaction, the optical potentials of Glassgold and Kellogg[21] (GK) are used since they are found to reproduce the elastic proton-nucleus scattering data quite well. To facilitate the comparison with the experimental data we have chosen the nonmagic nuclei ^{12}C and ^{28}Si and the magic ^{40}Ca. In order to study the off-shell influence with nuclear deformation, the unfactorized DWIA angular correlations are calculated for both spherical and nonspherical nuclei. The cross sections for ^{40}Ca and ^{28}Si are shown in

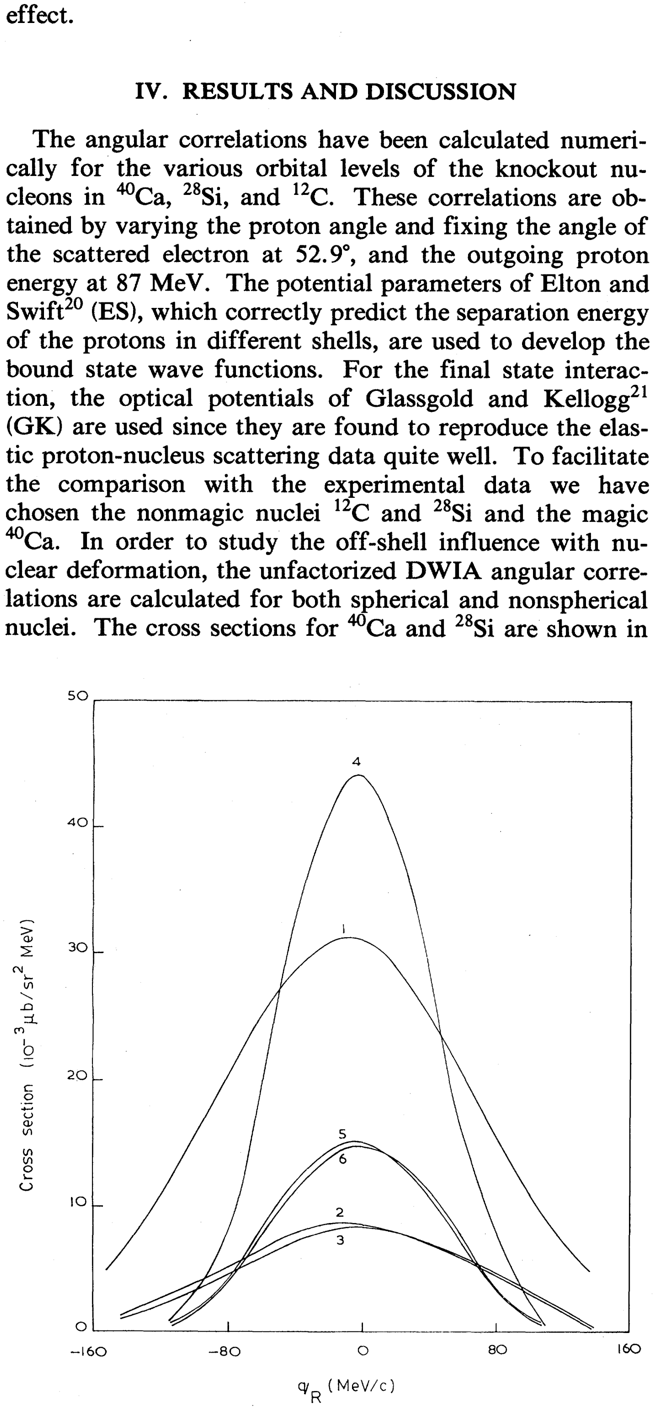

FIG. 1. Angular correlations for the $1s_{1/2}$ and $2s_{1/2}$ states of ^{40}Ca. Curves 1—3 correspond to the $1s_{1/2}$ state, while 4—6 correspond to the $2s_{1/2}$ state. (Curves 1 and 4, PWIA; curves 2 and 5, DWIA; and curves 3 and 6, DWIA with off-shell effect.)

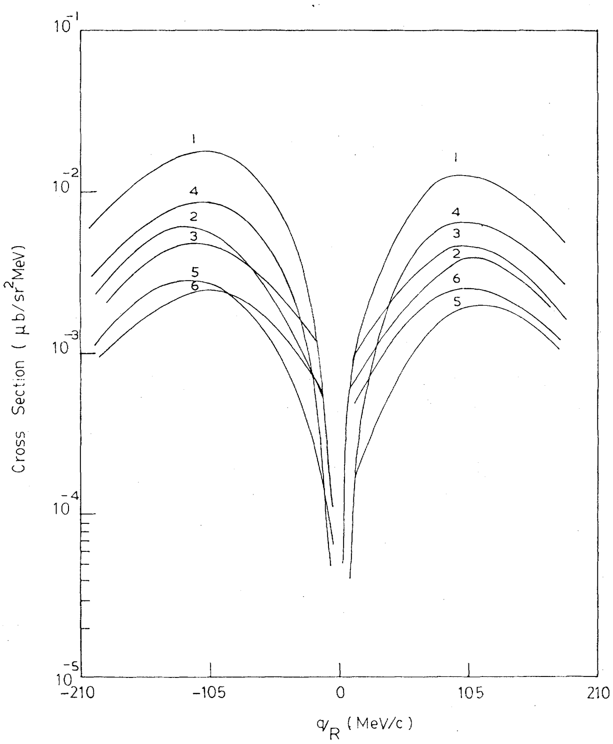

FIG. 2. Same as in Fig. 1 for ^{40}Ca. Curves 1—3 represent the $1p_{3/2}$ state, while 4—6 represent the $1p_{1/2}$ state.

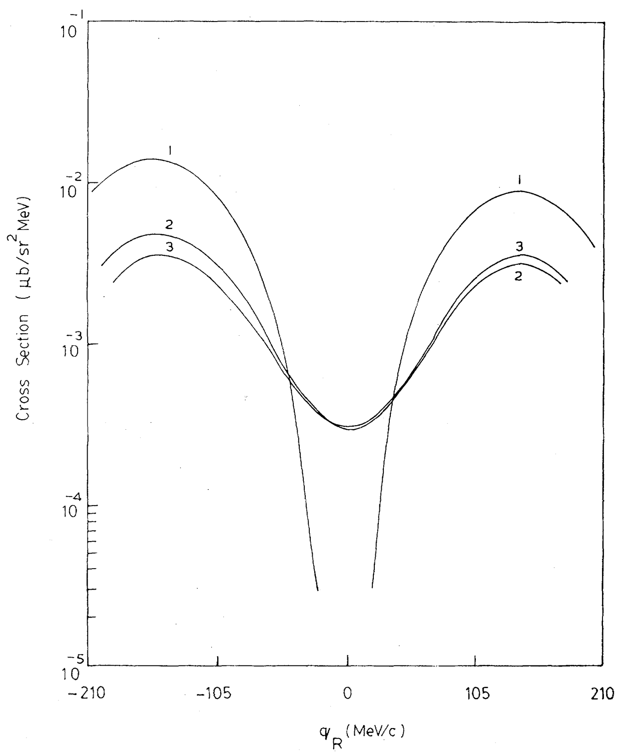

FIG. 4. Angular correlations for the $1d_{5/2}$ level of ^{28}Si. (Curve 1, PWIA; curve 2, DWIA; and curve 3, DWIA with off-shell effect.)

Figs. 1—4 and the result for ^{12}C has already been discussed.[7] The DWIA cross sections with and without the off-shell effect and the PWIA values are plotted in these figures. The off-shell effect reduces the cross section throughout the negative side of the recoil momentum, wherein the angle of the emitted proton is greater than the angle of momentum transfer. However, there is a slight increase in the cross section over the DWIA values in the positive side of the recoil momentum in which the proton angle is lower than the momentum transfer angle.

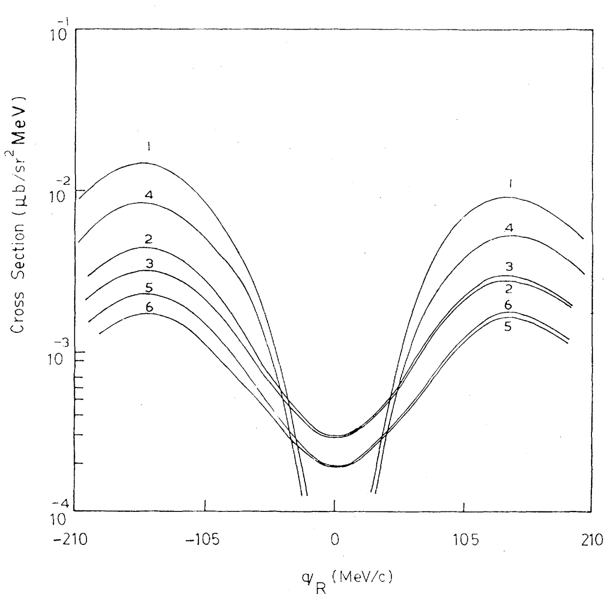

FIG. 3. Same as in Fig. 1 for the levels $1d_{5/2}$ (curves 1—3) and $1d_{3/2}$ (curves 4—6) of ^{40}Ca.

It has been found that the off-shell effect is more dominant in nonspherical nuclei than the spherical one since the reduction in the cross section is to increase with increase of nuclear deformation. A comparative study of the off-shell influence on different orbitals has also been performed. The average reduction factor between the DWIA and PWIA cross sections is calculated and compared with the experimental values of Mougey *et al.*[3] (Table I). The results indicate that the reduction factor increases from lower to higher orbital levels of the given nucleus and it also increases from spherical to nonspherical nuclei with a maximum reduction factor for ^{12}C. It is to be noted that the off-shell effect is to reduce the reduction factor for most of the orbital levels of the knockout nucleons and it is found to agree better with the experimental results.[3]

The effect of the spin-orbit coupling is introduced in the evaluation of the scattering amplitude through definite final angular momentum states $\vec{J}_f$ of the emitted proton. The optical potentials of Giannini and Ricco[22] (GR) and Jackson and Abdul-Jalil[23] (JA) are used to include the spin-orbit effect in the final state interaction.[24] While the GR potential contains only the real part of the spin-orbit component, the energy dependent potential of JA includes both the real and imaginary components. As evident from Fig. 5, the effect of these components is to affect the angular correlations only at the maxima and minima. The ES-JA potential with imaginary component gives a lower minimum and a higher maximum for the

TABLE I. Off-energy-shell effect on the reduction factor.

Nucleus	Orbital level	Reduction factor Without off-shell effect	With off-shell effect	Experimental value (Ref. 3)
	$1d_{3/2}$	0.3145	0.3030	
	$2s_{1/2}$	0.4165	0.3991	0.38
^{40}Ca	$1d_{5/2}$	0.3407	0.3248	
	$1p_{1/2}$	0.3264	0.3372	
	$1p_{3/2}$	0.3229	0.3385	0.32
	$1s_{1/2}$	0.2612	0.2570	0.23
	$1d_{5/2}$	0.3830	0.3646	
	$2s_{1/2}$	0.4925	0.4725	0.46
^{28}Si	$1p_{1/2}$	0.3595	0.3681	
	$1p_{3/2}$	0.3518	0.3560	0.39
	$1s_{1/2}$	0.3155	0.3041	0.28
^{12}C	$1p_{3/2}$	0.7205	0.6540	0.66
	$1s_{1/2}$	0.6755	0.5612	0.52

cross sections when compared with other potentials.

The factorized and unfactorized DWIA cross sections for ^{40}Ca are shown in Fig. 6. The factorized cross section, which is proportional to the spectral function, is obtained from the dominant Coulomb term of the interaction. In addition to the inclusion of all the terms of the interaction Hamiltonian, the unfactorized cross section takes care of the off-shell effect and the spin-orbit interaction. The contribution of various terms in the scattering amplitude and their relative significance have already been discussed in the PWIA.[2] Since the electron field interacts with nuclear currents and magnetic momenta as well, one must include all interactions and interference terms between them.[25] The results indicate that besides the enhancement of the absolute value, the unfactorized cross section produces a possible asymmetry with respect to the proton angle (recoil momentum).

The missing energy spectrum is calculated for ^{12}C in

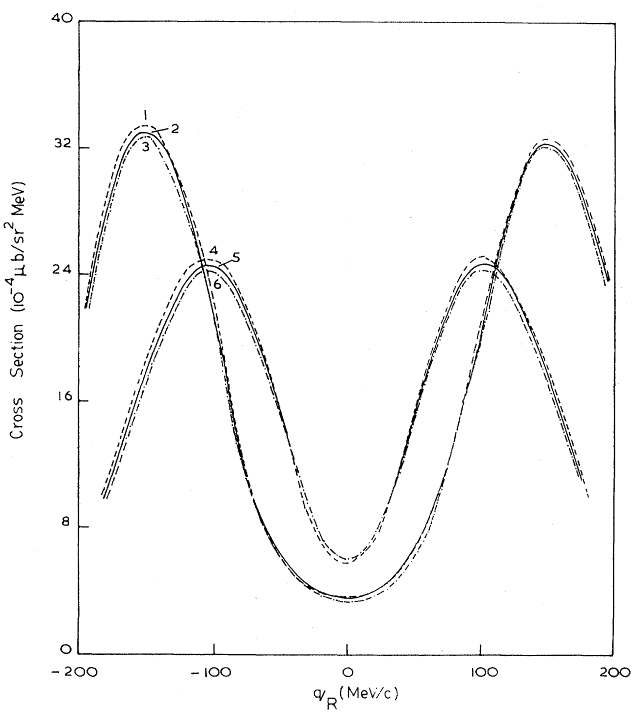

FIG. 5. Angular correlations for the $1p_{1/2}$ (curves 1—3) and $1d_{5/2}$ (curves 4—6) levels of ^{40}Ca. While curves 1 and 4 include both real and imaginary spin-orbit components, curves 3 and 6 include only real components. Curves 2 and 5 do not include both the components.

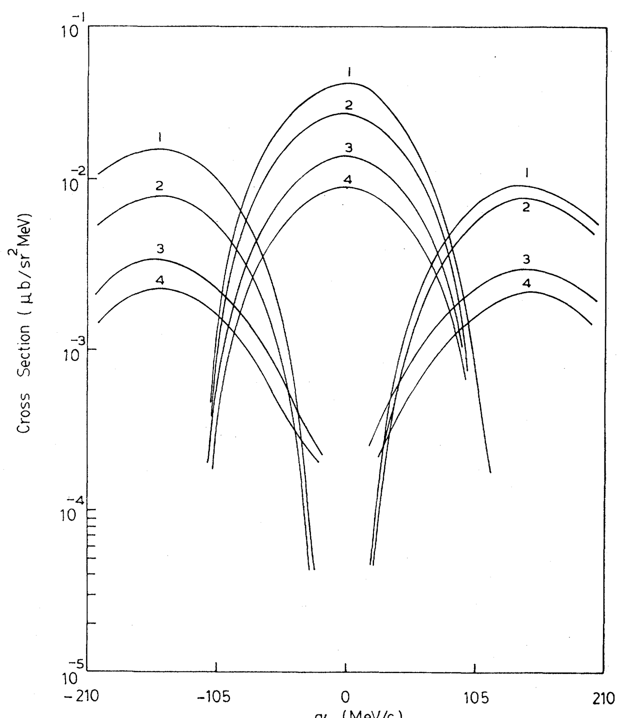

FIG. 6. The single and double hump curves correspond to $2s_{1/2}$ and $1d_{5/2}$ levels of ^{40}Ca. Curves 1 and 3 correspond to unfactorized PWIA and DWIA calculations whereas curves 2 and 4 correspond to factorized PWIA and DWIA results.

the unfactorized DWIA approach. The kinetic energy of the proton is taken as 110 MeV and the angles of the outgoing proton and electron are fixed at 60° and 51°, respectively. These values are chosen to correspond to the experimental work of Amaldi.[17] The position of the peaks in the spectrum are identified with the separation energies of 16 and 37 MeV corresponding to $p_{3/2}$ and $s_{1/2}$ states of ^{12}C, which are obtained by solving the bound state problem with suitable potential parameters. For the Gaussian, the full width at half maximum is taken as $\Gamma s = 19.8$ MeV and $\Gamma p = 6.9$ MeV for $s_{1/2}$ and $p_{3/2}$ states. As seen from the energy spectrum of ^{12}C (Fig. 7), the inclusion of the off-shell effect produces a predominant reduction in the cross section at the peak corresponding to the p state. The results are compared with earlier work[19] wherein only the Coulomb term of the interaction is considered, which, however, is only approximate and incomplete. Besides leaving the spin-orbit coupling, the earlier result neglects the off-shell effect also. In the figure, the curve with the off-shell effect is normalized to the experimental peak position at $E_s = 16$ MeV and other curves are multiplied by the same constant throughout. The experimental data are taken from the work of Amaldi.[17]

In Fig. 8, the influence of the different choices of bound and scattering potentials is shown on the missing energy spectrum of ^{12}C. While the Woods-Saxon form of ES and GR potentials are used for the bound state, the optical potentials of GK, GR, and JA are employed for the final state interaction. The choice of potential parameters is seen to affect the energy spectrum only at the peaks and it is found that the JA potential with both real and imaginary spin-orbit components produces a marked dip in the cross section at the peak corresponding to the p state. In Fig. 8, the curve corresponding to the potential of ES-GK is normalized to the experimental peak.

The present study on the angular correlations and energy spectrum of the quasifree electron scattering stresses the importance of the unfactorized DWIA approach in the nonrelativistic description wherein all the finer details of the process are accounted for in an effective manner. The comparison between the factorized and unfactorized calculation shows that the unfactorized cross section not only accounts for the absolute value but also for the possible asymmetry in its distribution. Since the contribution of the convective current term[2] to the cross section is about 30%, the off-energy shell influence which affects that term is not negligible, but its contribution is expected to vanish for electron momentum transfer $q = 0$ because of the transverse current effect. Nevertheless, the source of the off-shell effect is not only the convection current term but also the kinematics of the problem and both these are inextricably mixed. The nuclear recoil momentum $q_R = 0$ corresponds to zero momentum of the target nucleon as per the impulse approximation but it does not necessarily imply that the off-shell effect is zero. The results of the angular correlation indicate that the effect vanishes only for some positive value of q_R and not exactly at $q_R = 0$. This shift or asymmetry with respect to the proton angle (recoil momentum) is a specific effect due to the unfactorized DWIA approach. The variation of the

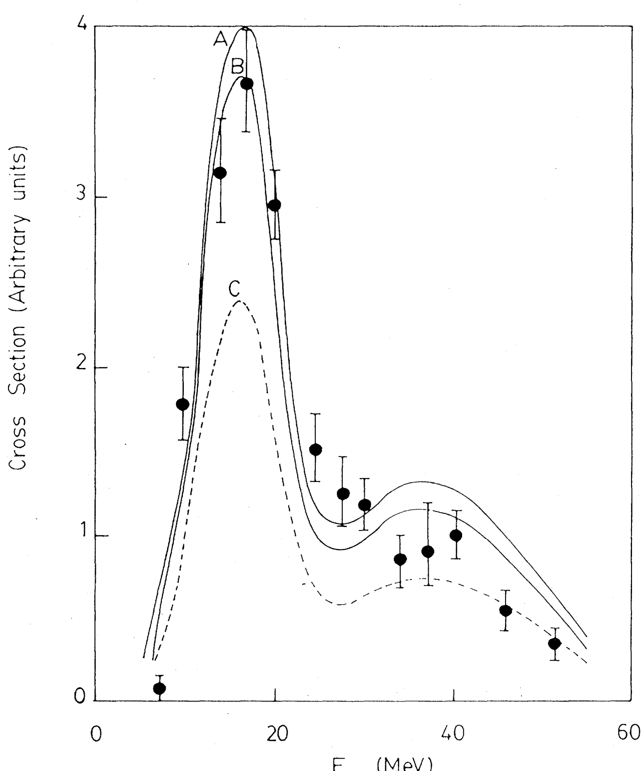

FIG. 7. Missing energy spectrum of ^{12}C in DWIA. Curves B and A are drawn with and without the off-shell effect. Curve C includes only the Coulomb term of the interaction.

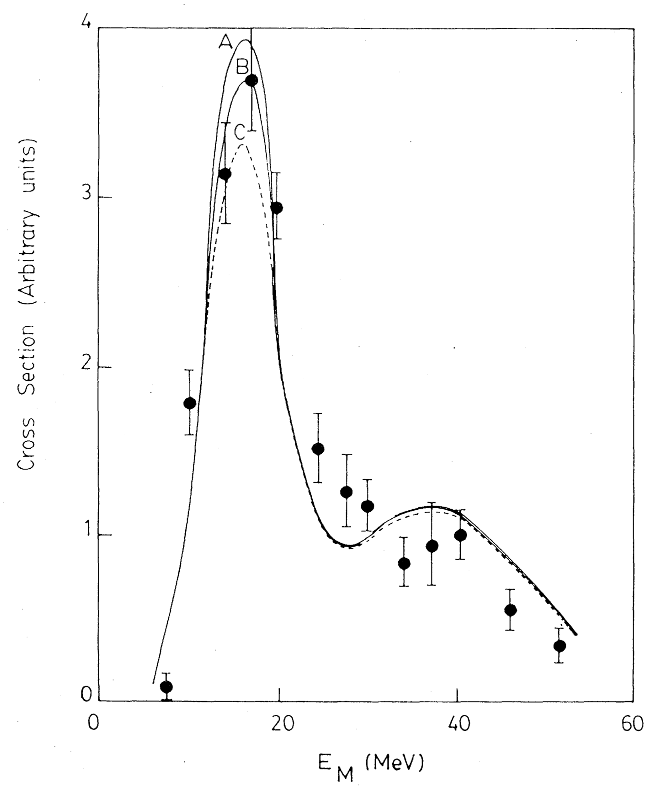

FIG. 8. Missing energy spectrum of ^{12}C. The curves A–C represent the DWIA calculations with GR-GR, ES-GK, and ES-JA potential parameters.

nucleon momentum through the nuclear medium is more precisely incorporated when the off-shell effect is simulated by the gradient operator $\vec{\nabla}$. The comparative study on spherical and nonspherical nuclei reveals that the off-shell influence is to increase with the increase of nuclear deformation. The unfactorized approach with this influence is found to reduce the average reduction factor closer to experimental values for various orbital levels of the knockout proton. The study of the energy spectrum brings out the inadequacies of earlier methods[18,19] and justifies the validity of the unfactorized approach. The spin-orbit term with real and imaginary components of different choices of optical potentials is found to affect the cross sections around the maxima and minima. The calculated angular correlations and energy spectrum values are found to be much influenced by the finer aspects of the present approach and are quite different from earlier results.

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