MULTISTEP DIRECT PROCESSES IN NUCLEON KNOCKOUT REACTIONS*

G.F. Steyn[a], A.A. Cowley[b], S.V. Förtsch[a], J.J. Lawrie[a], W.A. Richter[b], and S.W. Steyn[b]

[a]National Accelerator Centre
P.O. Box 72, Faure 7131, South Africa
[b]Department of Physics, University of Stellenbosch
Stellenbosch 7600, South Africa

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The success of statistical multistep direct (MSD) theories in describing continuum cross sections in inclusive $(p,\, p')$ reactions is important for understanding preequilibrium emission from the continuum in exclusive $(p,\, p'p'')$ reactions. This ensures the accurate prediction of the contribution of the rescattering background to other processes, such as deep-lying hole states populated in discrete knockout of nucleons.

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1. Introduction

Preequilibrium nucleon emission was identified to be an important process in the interaction of energetic light projectiles with atomic nuclei approximately three decades ago [1]. Subsequent experimental investigations mostly explored inclusive reactions. The concurrent development of appropriate theoretical models to interpret these data led to several semiclassical formulations [1] and later to the quantum-mechanical multistep theories [1, 2]. The statistical multistep direct (MSD) theory of Feshbach, Kerman and Koonin (FKK) [3,4], for example, has found wide application in the description of cross sections and angular distributions in inclusive $(p,\, p')$ reactions.

Cross sections for coincident-particle emission in proton-induced reactions were measured in some experiments with kinematics specifically optimized for the study of the preequilibrium process [5–11]. A theoretical formalism developed by Ciangaru [6, 7, 12] extended the ideas of the FKK

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theory to the $(p, p'p'')$ reaction. The theory assumes an initial quasifree nucleon-nucleon (N-N) interaction between the projectile and a target nucleon, leading to two energetic nucleons which will generally suffer further N-N collisions as they traverse the residual nucleus. To simplify the analysis, the kinematic conditions of a coincidence experiment can be chosen in such a way that it becomes unlikely for the scattered projectile (hereafter referred to as the primary emitted proton) to have suffered more than the one violent collision with the struck target nucleon. The struck nucleon can then be viewed as an intranuclear projectile and its subsequent rescattering has to be taken into account explicitly. An assumption of the model is that the intranuclear projectile behaves as an external projectile incident upon the residual nucleus. The coincidence continuum cross section then follows from the convolution integral over the quasifree knockout cross section for the initial N-N interaction and an appropriately normalized multistep cross section describing the rescattering process. Consequently the Ciangaru model is a marriage of the distorted-wave impuls approximation (DWIA) which has been extensively employed in discrete knockout reactions and the MSD theory which has been found to be invaluable in the study of inclusive reactions.

A study of proton-induced coincident proton emission from the continuum is important because multiple scattering processes give rise to a rescattering background upon which other nuclear phenomena are superimposed. This background may interfere with the observation of these other processes. Typical examples are giant resonances and the population of deep-lying hole states by means of discrete knockout from deeply-bound shell model orbitals.

Ciangaru *et al.* [7] speculated that their model may be suitable for extracting the rescattering background underlying deep-lying hole-state knockout data. This was recently investigated by Cowley *et al.* [13] for the ^{40}Ca$(p, p'p'')$ reaction at an incident energy of 392 MeV. The rescattering background was studied at excitation energies extending to the $1s$ and $1p$ hole states, which were clearly resolved. The conclusions of Ref. [13] depend critically on the ability of MSD calculations to predict differential cross sections for the inclusive ^{40}Ca(p, p') reaction at incident energies similar to that transferred to the intranuclear projectile in the initial N-N interaction. An example of the available data for this reaction with corresponding MSD predictions will therefore be included in this presentation to clarify this point.

A related area of concern is the extent to which rescattering effects may influence current experimental investigations of polarization observables in discrete knockout reactions, which may be more severe than in the case of cross section measurements. It is clear that an appropriate evaluation of these possibly interfering effects can only be made if the reaction mechanism for the rescattering process is understood well.

2. The Ciangaru formalism

In the simplified case for a single intranuclear projectile the coincident continuum cross section of the reaction A(a, $a'b$)B can be expressed as follows:

$$\frac{d^4\sigma\left(\Omega_b E_b \Omega_{a'} E_{a'}\right)}{d\Omega_{a'} d\Omega_b dE_{a'} dE_b} = \sum_{\mathrm{N}} \left[\int d\Omega_{b'} \sum_{\lambda} \left\{ \frac{d^3\sigma_{\lambda}^{\mathrm{QF}}\left(\Omega_{b'} E_{b'} \Omega_{a'} E_{a'}\right)}{d\Omega_{a'} d\Omega_{b'} dE_{a'}} \right\} \left\{ \frac{1}{\sigma_{\mathrm{N}}\left(E'_b\right)} \frac{d^2\sigma^{\mathrm{RC}}\left(\gamma E_b E_{b'}\right)}{d\Omega_{b-b'} dE_b} \right\} \right].$$

The primary observed proton is denoted by a', the struck nucleon by b' and the secondary observed proton by b. The summations are separately evaluated for protons and neutrons, denoted by N, which are initially bound in shell-model orbitals λ in the target. The triple differential cross section in the integrand is the three-body DWIA cross section for the quasifree knockout (QF) mechanism, but without distortion in the wave function of the knocked-out nucleon b'. It is reasoned that this distortion is included implicitly in the rescattering chain (RC) of the struck nucleon, as expressed by the double differential cross section in the integrand. The quantity σ_N is the total reaction cross section for the (b', b) reaction with the residual nucleus induced by an intranuclear projectile b' at an energy $E_{b'}$ as defined by energy conservation after the initial N-N interaction. The normalized expression for the rescattering chain essentially becomes the inelastic scattering probability for the intranuclear projectile. The angle between the directions of the struck nucleon and the secondary observed proton is denoted by γ. The integration is over the solid angle of the struck nucleon.

3. The multiple scattering chain

The FKK theory of multistep direct emission as applied to proton-induced reactions assumes an initial two-body N-N interaction between the incoming proton and a target nucleon, thereby exciting the target nucleus to a one-particle-one-hole (1p-1h) state. This is the first step of the multiple scattering chain. The chaining hypothesis asserts that subsequent stages (or steps) in the excitation of the nucleus proceed via successive particle-hole excitations in such a way that the complexity of the particle-hole state will not be changed by more than one unit in a particular step. This is equivalent to assuming that a transition from stage n to stage $n+1$ can only be induced by a further two-body N-N interaction. The never-come-back assumption is often applied, *i.e.* that each successive step will increase the complexity of the state. Emission of a preequilibrium nucleon into the continuum may take place after each step. The process can in principle continue until the nucleus becomes fully equilibrated.

Angular distributions for the ^{40}Ca(p, p') reaction measured at an incident energy of 165 MeV [14] are shown in Fig. 1 for various emission energies. MSD calculations based on the implementation of the FKK theory by Bonetti and Chiesa [15] are also shown. In spite of some discrepancies, the theoretical predictions reproduce the data reasonably well.

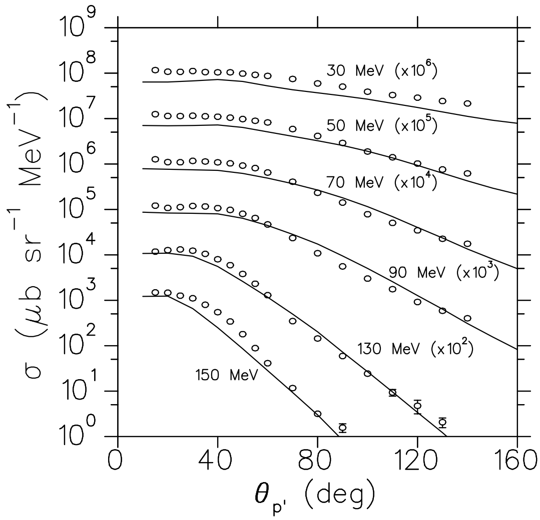

Fig. 1. Experimental angular distributions for the ^{40}Ca(p, p') reaction at an incident energy of 165 MeV, for various emission energies $E_{p'}$. The curves are results of MSD calculations based on the formulation of Feshbach, Kerman and Koonin [3]. Results are multiplied by the factors indicated in brackets for display purposes and are given in the laboratory system. Error bars are shown only when these exceed the symbol size.

4. Studies between 100 and 200 MeV

Studies of the (p, $p'p''$) reaction on ^{58}Ni [5–7] at 100 and 200 MeV, ^{12}C [9] at 200 MeV and ^{197}Au [11] at 200 MeV confirmed the role of an initial quasifree knockout process as a precursor to the emission of preequilibrium particles above the threshold of a three-body breakup process. The Ciangaru model was also shown to qualitatively reproduce the coincident proton cross sections. With the exception of the study on the lightest target nucleus (^{12}C), to a large extent only the valence nucleons appear to contribute in the reaction. This may simply be due to the large distortion associated with the knockout from the more deeply-bound shells at these relatively low incident energies. Clearly, investigations at higher incident energies are required to observe the participation of deeper states.

5. A study at a higher incident energy

The ^{40}Ca(p, $p'p''$) reaction was recently investigated at an incident energy of 392 MeV in a kinematic and angular range optimized for a study of the rescattering process as well as observing the population of deep-lying hole states [13]. ^{40}Ca was chosen as target because single particle spectroscopic information is reasonably well known for this nucleus, even to the deepest shell-model orbitals. The primary protons were observed at a scattering angle of 25.5° in a narrow energy region of 20 MeV in width, centered around 220 MeV. The secondary protons were measured at scattering angles of 25.5°, 40°, 60°, 80°, 100° and 120° on the opposite side of the beam, from a threshold of about 50 MeV up to the kinematic limit. Further details of the experiment, which was performed at the Research Centre for Nuclear Physics (RCNP) in Japan (using a dual magnetic spectrometer system), can be found in Ref. [13].

The knockout cross section was calculated using the well known DWIA code THREEDEE of Chant and Roos [17]. Relative spectroscopic factors for the initial knockout process were based on the single particle shell model spectroscopic sum rule limit, except for the $1f_{7/2}$ state, which had to be scaled to experimental results of Doll *et al.* [16]. The overall spectroscopic strength was subsequently adjusted to give a fair representation of the cross sections observed for knockout to discrete valence states in that work. This procedure then fixes the absolute magnitude of the initial interaction that serves as a source reaction to the rescattering process of the struck nucleon. For the rescattering of the struck nucleons, interpolated values of the available inclusive (p, p') experimental data [14] (some of which are shown in Fig. 1) were used, rather than the MSD predictions. This was done in order to ascertain possible deficiencies in the Ciangaru formalism more accurately, rather than to transmit the known deviations (albeit relatively small) of the MSD cross sections to the theoretical predictions in this case. Further details of the calculations are given in Ref. [13].

In Fig. 2 experimental data from Ref. [13] over the complete range in binding energy are shown, together with theoretical cross sections for the ^{40}Ca(p, $p'p''$) reaction, which forms a background upon which yields of the (p,2p) reaction to discrete states are superimposed. At angles of 80° and beyond, knockout to discrete states is not observed and the measured data only reflect the rescattering background. This is consistent with the rapid fall-off predicted by the DWIA theory for the (p, 2p) source reaction. The ability of the DWIA theory (added to the rescattering background) to reproduce the experimental binding energy spectra for deep-lying hole states excited in the (p, 2p) reaction is illustrated in Fig. 3. Results are shown with widths and positions of the 1s and 1p states taken from the experi-

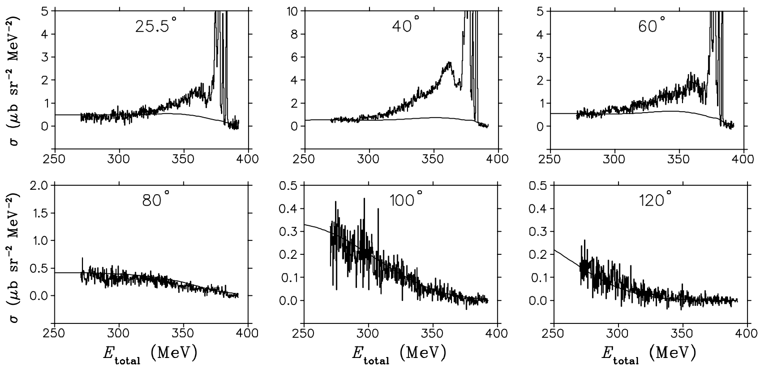

Fig. 2. Binding-energy spectra for the ^{40}Ca(p, $p'p''$) reaction at 392 MeV. The curves represent the rescattering background according to the theory of Ciangaru. (Taken from Ref. [13].)

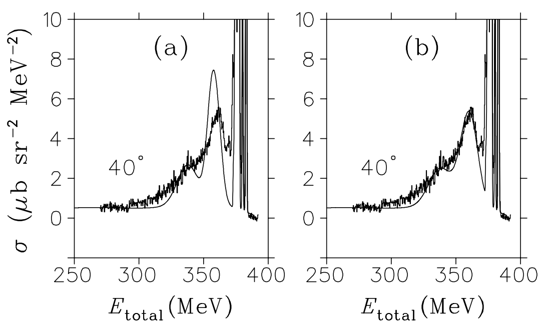

Fig. 3. As in Fig. 2 at 40°, but the curves represent the sum of discrete knockout for the 1s and 1p states and rescattering component. See text for full explanation. (Taken from Ref. [13].)

mental work of Volkov *et al.* [18] (Fig. 3(a)), as well as the results obtained if these quantities are adjusted for better agreement with the experimental data (Fig. 3(b)). The absolute knockout yields, however, are the same in both cases.

6. Conclusions

An example is shown illustrating that inclusive (p, p') data are reproduced reasonably well by MSD calculations. This theoretically-based understanding of the (p, p') component of the Ciangaru formalism for the (p, $p'p''$) reaction is reassuring. The theoretical treatment of the knockout part, which is the other crucial ingredient in the description of the (p, $p'p''$) reaction, is also known to be reliable. Consequently the contribution of the rescattering background to other processes, such as discrete knockout of nucleons from deeply-bound shell model orbitals, is clearly predictable with a high degree of accuracy. The successful evaluation of this new calculational tool is especially significant for future studies of in-medium effects on the nucleon-nucleon interaction.

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