MULTISTEP DIRECT PROCESSES IN POLARIZATION PHENOMENA AND COMPOSITE PARTICLE EMISSION*

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The statistical multistep theory of Feshbach, Kerman and Koonin has established itself in describing proton-induced preequilibrium reactions over a wide angular range up to an incident energy of 200 MeV. Extensions to the theory made it possible to also predict both the continuum cross sections and analysing powers of the $(\vec{p},p')$, $(\vec{p},\alpha)$ and $(\vec{p},{}^3\mathrm{He})$ reactions at incident energies below 100 MeV. These reactions were recently also measured at incident energies above 100 MeV, thus providing further testing grounds of the inferred multistep reaction mechanism.

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1. Introduction

The nucleon-nucleon (N-N) interaction and its modifications due to medium effects of nuclear matter continues to be a focus point in studies of reactions induced by energetic protons up to a few hundred MeV with

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atomic nuclei. Especially the inclusive $(p,p'X)$ reaction was studied extensively both experimentally and theoretically. Various theoretical models were introduced to describe the experimental cross sections. Most of these models [1] treat the reaction mechanism in terms of a succession of N-N collisions with particles being emitted at various stages as the projectile energy is progressively dissipated in the target nucleus. As the mass of the target nucleus increases and the higher incident energy is shared among the target nucleons, it becomes increasingly important to include more steps.

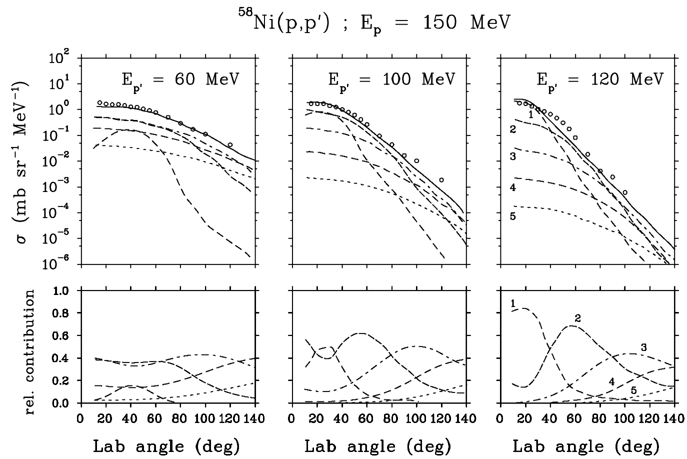

Fig. 1. Emission energy dependence of the absolute (upper panels) and relative contributions of the leading five MSD steps to the angular distributions. The step number is indicated as labels of the various dashed curves in the right-hand panels. The solid curves represent the sums of the indicated step contributions. These results are taken from Ref. [6].

Considerable progress has been made towards understanding particularly the differential cross sections when applying the statistical multistep direct (MSD) theory of Feshbach, Kerman and Koonin (FKK) [2]. An important extension to the theory was made by Chadwick and co-workers [3] by including multiple preequilibrium emission in the FKK analysis of inclusive nucleon induced spectra above an incident energy of 50 MeV. Satisfactory agreement between theory (using the MSD code of Bonetti and Chiesa [4]) and experiment is obtained especially for the medium to heavy mass nuclei between incident energies of 80 and 200 MeV [5–8] (see Fig. 1). At these energies the calculations are being extended to lighter target nuclei as well as the emission of complex particles to the continuum. Efforts are also underway to apply the theory to continuum analysing powers of the inclusive $(\vec{p},p'X)$ reaction at incident energies above 100 MeV. Experimental polarization data provide a stringent test of the theory, being more sensitive to the detail of the reaction mechanism than differential cross sections. Both in nucleon and composite particle emission to the continuum, the importance of understanding the analysing powers is currently setting the trend in this field.

2. Preequilibrium cluster emission

In the work of Bonetti *et al.* [9] it was shown that the FKK theory can also be applied to describe α-particle emission in preequilibrium reactions at incident energies well below 100 MeV. Since then Olaniyi *et al.* [10] and Guazzoni *et al.* [11] have used the same quantum-mechanical multistep formalism of α-particle knockout to describe inclusive (p,α) spectra for medium to heavy-mass nuclei. Here the assumption is made that the α particle is preformed and bound inside the nucleus prior to being knocked out by a nucleon, rather than that the α emission takes place via a pickup mechanism of a triton. This is in agreement with Ref. [9] and seems to be valid

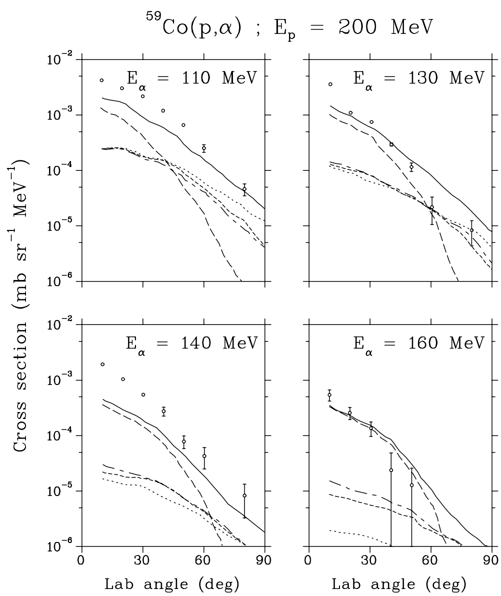

Fig. 2. Lab. angular distributions at various α-particle emission energies E_α as indicated, compared with MSD calculations. The long dashed curves are first-step (p,α) knockout contributions. The contributions for $(p,p')(p',\alpha)$ (short dashed) and $(p,n)(n,\alpha)$ (dot-dashed) are indicated separately, with the dotted curve representing the sum of three-step contributions. The summed cross sections are given by the solid curves. The negligible c.m. motion is within the experimental uncertainties. These results are taken from Ref. [12].

even at energies between 30 and 44 MeV. Recently these calculations were compared to experimental cross sections of the (p, α) [12] and $(p,^3\mathrm{He})$ [13] reactions on ^{27}Al, ^{59}Co, and ^{197}Au at incident energies of 120, 160, and 200 MeV. At these energies it is shown that higher order steps like the three-step process $(p,p')(p',p'')(p'',\alpha)$ become progressively more important as the emission energy decreases, as is illustrated in Fig. 2. Furthermore, the possibility that both the proton and α particle can in principle be unbound after the interaction due to phase space arguments were included in these calculations. Results of the calculations for the $(p,^3\mathrm{He})$ reaction [13] seem to suggest that the dominant contribution at excitation energies of more than $\sim$30 MeV originates from a pickup of a bound deuteron after at least two successive N-N collisions. Both these studies appeal for more theoretical refinements, which should be facilitated by analysing power measurements and their interpretations.

3. Continuum analysing powers

While Bonetti *et al.* [14] have used the FKK theory to describe both the cross sections and the analysing powers of the $^{58}\mathrm{Ni}(\vec{p},p')$ reaction at 65 MeV, the applicability of the theory at higher incident energies is investigated at present by studying angular distributions of continuum analysing powers in the energy region between 100 and 200 MeV.

In order to improve the ability of the FKK theory to predict continuum analysing powers, a recently developed fully microscopic effective N-N interaction [15] is being implemented in the MSD code. It is suggested that this interaction, which reproduces elastic scattering data and analysing powers at the incident energies of interest, replaces the short-range Yukawa interaction in order to include spin-parity and isospin effects in the two-body N-N interaction.

While these theoretical extensions are currently in progress, an alternative method is used here for a preliminary interpretation of the analysing power, whereby only the first (*i.e.* a single) step is considered. Following procedures reported in Ref. [16], the first step is described in terms of a quasifree scattering mechanism and is calculated with the distorted wave impulse approximation (DWIA) [17]. The validity of this procedure in estimating the first-step contribution is confirmed, in that the quasifree knockout cross section is quantitatively very similar to the first-step prediction of the FKK theory for the $^{24}\mathrm{Mg}(p,p')$ reaction at an incident energy of 186 MeV, as shown in Fig. 3.

Continuum $^{24}\mathrm{Mg}(\vec{p},p')$ analysing powers were measured at incident energies of 150 and 186 MeV [18]. The 186 MeV data are shown in Fig. 4 as angular distributions at various ejectile energies. The general trend of the

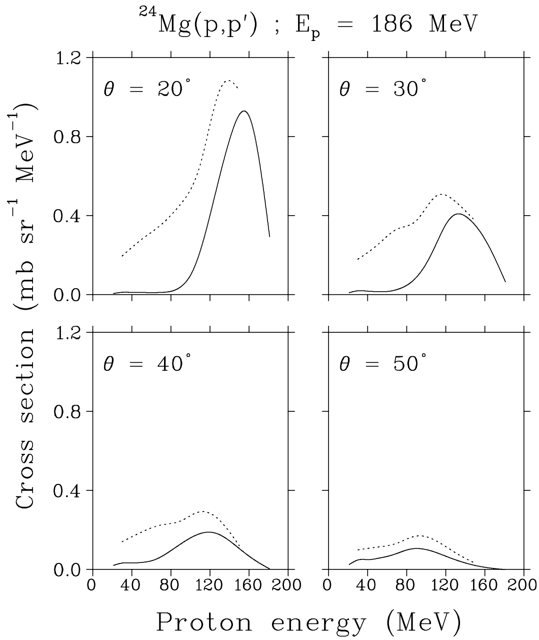

Fig. 3. Comparison between first step MSD calculations (solid lines) and quasifree-knockout distributions as calculated in DWIA (dotted lines) at scattering angles as indicated.

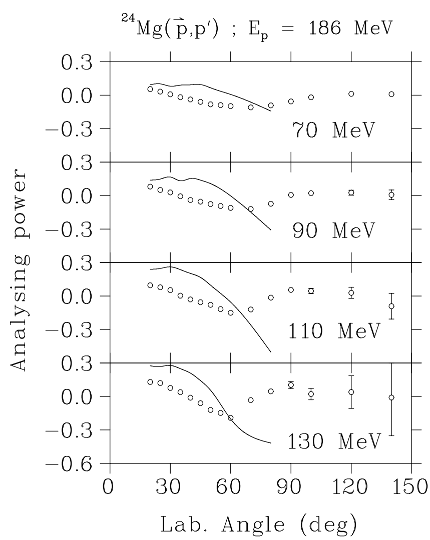

Fig. 4. Lab. angular distributions of continuum analysing powers at emission energies as indicated. The curves are DWIA calculations.

continuum analysing powers both at 150 and 186 MeV is in agreement with similar measurements at 65 MeV of Sakai *et al.* [19] except at the very backward angles, where the results of Ref. [19] are characterised by large positive analysing powers. At these large scattering angles the multistep contributions seem to neutralize the initial polarization, emphasizing the dominance of the higher order steps in cross section calculations. The comparison with the single-step DWIA analysing powers (see Fig. 4) suggests that a quasifree scattering mechanism manifests itself predominantly at forward angles as illustrated *e.g.* in Ref. [20]. Contributions from the multistep part to the measured analysing powers dilute the first step with increasing angle and excitation energy, which is consistent with the relative importance of the higher order stages in the scattering chain in reproducing the data [14].

Although the FKK theory clearly provides the complete model and interpretation of the physics, this alternative and much simpler approach indicates the importance of an initial quasifree N-N interaction, in spite of the large multiple scattering background which obscures the single-step signature to a large extent. Certain implications of this process whereby two particles are scattered into the continuum after the initial N-N interaction, have been suggested as extensions to the MSD model [3].

In the case of continuum analysing powers of complex particles, higher order steps seem to become increasingly important as the incident energy increases. Measurements of analysing powers of α particles and various intermediate mass fragments emitted at forward angles from the reaction of 200 MeV polarised protons on $^{\rm nat}$Ag, performed by Renshaw *et al.* [21], provide no evidence for significant contributions from a one-step cluster knockout process, while Bonetti *et al.* [9] applied the knockout model using a one-step reaction only, to describe the analysing powers of the ^{58}Ni$(\vec{p},\alpha)$ reaction at an incident energy of 72 MeV. In order to investigate this observed trend further, more experimental data are required in the form of full angular distributions at incident energies between 100 and 200 MeV. Ultimately, calculations with the MSD theory will provide a more complete interpretation of the reaction mechanisms involved.

4. Summary and future prospectives

Calculations based on the multistep direct theory of Feshbach, Kerman and Koonin for a wide variety of targets and incident energies have been shown to account for measured inclusive proton and complex particle emission spectra up to 200 MeV. Present uncertainties regarding the detail of the calculations include the treatment of the two-body interaction in the nuclear medium, the distinction between protons and neutrons and their spin properties, the rigorous inclusion of more than one continuum particle, the use of appropriate optical potentials and level densities at high excitations and the inclusion of relativistic effects. The next stringent test of the theory and the inferred reaction mechanism is the consistent interpretation of both the measured $(\vec{p}, p'X)$ continuum cross sections and analysing powers at the higher incident energies.

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