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Recent Conclusions from Proton-Induced ^{3}He- and α-Emission into the Continuum

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Abstract. The basic reaction mechanism of proton-induced composite particle emission as a statistical multistep pre-equilibrium process has been identified and confirmed long ago. However, many important details were until fairly recently still obscure. Valuable insight into the mechanism of (p,α) and (p,^{3}He) reactions only became available with our work during the last four years. An overview of results and conclusions based on these studies at incident energies from 65 to 200 MeV are presented and evaluated. Future avenues of investigation are discussed.

1 Introduction

The exciton model of Griffin [1] many years ago launched the progress towards the present understanding of the mechanism of nucleon-induced pre-equilibrium reactions [2]. The insight provided by the classical exciton model was crucial to development of quantum-mechanical statistical multistep formulations, such as those of Feshbach *et al.* [3, 4], Tamura *et al.* [5], and Nishioka *et al.* [6], which were proposed later. In terms of these models the pre-equilibrium reaction proceeds as a statistical multistep process in which nucleons and composite ejectiles escape from the nuclear system as it develops towards equilibration. Although the basic mechanism is not in dispute, finer details for especially composite ejectiles such as ^{3}He and α particles need further clarification. For example, in (p,α) pre-equilibrium reactions the competition between knockout and pickup processes still needs to be evaluated more carefully in terms of its dependence on target species and incident energy. As will become apparent in this review, existing studies suffer from a paucity of experimental data.

In this paper additional information on the mechanism of nucleon-induced pre-equilibrium reactions is offered. Our published results, especially those over the last four years, are interpreted in a consistent and unified way. In this respect, our recent work on (p,α) reactions will be highlighted as being of significant current interest.

Some of the ideas presented here were recently discussed at scientific meetings [7–9] in various contexts, but additional details are provided now.

2 Pre-Equilibrium Cross Section Angular Distributions

Typical examples of angular distributions for (p,p'), (p,^{3}He) and (p,α) are shown in Figures 1 and 2. In Figure 1 the experimental data are compared with the predictions of the theory of Feshbach, Kerman and Koonin (FKK) [3]. In order to illustrate the simple systematics involved, the data for emission of ^{3}He and α particles in Figure 2 are compared with a purely phenomenological prediction developed by Kalbach [10]. This shows the angular variation of the cross section $\frac{d^2\sigma}{d\Omega dE_b}$ with emission energy E_b to obey the expression

$$\frac{d^2\sigma}{d\Omega dE_b} = \sigma_D \frac{\eta}{\sinh\eta}\exp(\eta\cos\theta), \tag{1}$$

where $4\pi\sigma_D$ is the total angle-integrated cross section for a specific type of pre-equilibrium reaction, θ is the scattering angle and η is a slope parameter which is a simple power function of E_b.

The systematic trend shows that, at high emission energy, the cross section drops steeply with θ, as would be expected for the highly-direct nature of the

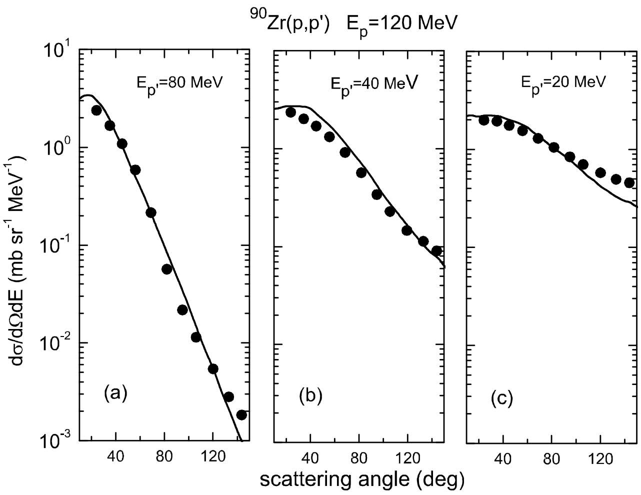

Figure 1. Cross section angular distributions for the reaction ^{90}Zr(p,p') at an incident energy of 120 MeV and ejectile energies as indicated in panels (a), (b) and (c). The curves are predictions of the FKK theory. Results are adapted from Ref. [11].

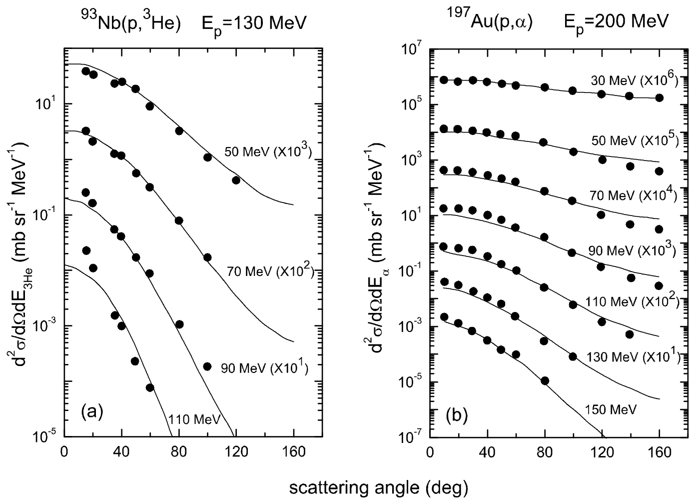

Figure 2. Cross section angular distributions (a) for the reaction ^{93}Nb(p,^{3}He) at an incident energy of 130 MeV and (b) for the reaction ^{197}Au(p,α) at an incident energy of 200 MeV. Ejectile energies are shown with each distribution and cross sections are multiplied by the indicated factors for clarity of display. The curves are predictions of the systematics expressed in Eq. 1. Results in (a) are derived from Ref. [12] and those in (b) from Ref. [13].

initial stage of the reaction chain. As the emission energy drops, the rate of decrease with θ of the cross section becomes less prominent. This reflects the growth of number of stages of the reaction process, which eventually would reach an isotropic (or symmetric around 90°) angular distribution as equilibration is reached.

The simple trend of the cross section angular distribution hints at a fundamental relationship of the reaction mechanisms common to any of the ejectiles shown in Figures 1 and 2. However, it also suggests that the cross section distributions would not be very sensitive to differences in, for example, target mass.

3 Analyzing Power Angular Distributions

The analyzing power is given by

$$A_y = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}, \tag{2}$$

where σ_L and σ_R are directions left and right in a coordinate system which has the Z-axis in the direction of the projectile momentum, and projectile polarized perpendicular to the reaction plane defined by Y-Z. The analyzing power angular distribution is much more sensitive to the multistep character of a preequilibrium reaction, as shown for example in Figure 3 for ^{93}Nb(p,^{3}He) at an

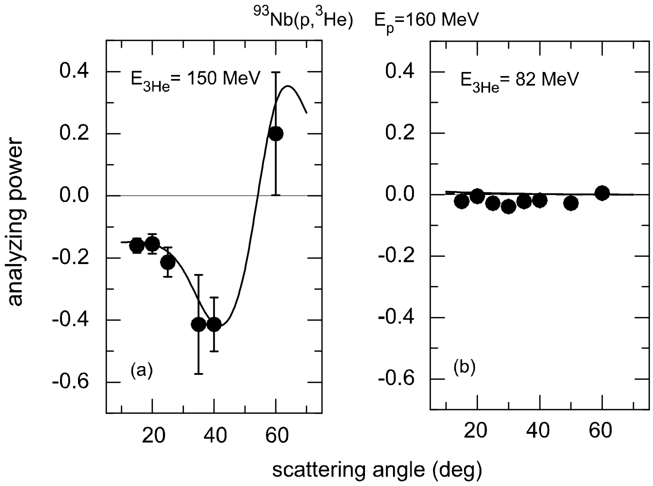

Figure 3. Analyzing power angular distributions for the reaction ^{93}Nb(p,^{3}He) at an incident energy of 160 MeV and emission energies of (a) 150 MeV and (b) 82 MeV. The curves are predictions of the FKK theory. Results are from Ref. [14].

incident energy of 160 MeV. Whereas the slopes of the cross section angular distributions change only in a subtle way with higher steps in the reaction stage [14], analyzing power distributions change shape rapidly. For example, at the highest emission energy where the first stage is dominant in Figure 3, the analyzing power distribution shows large excursions from zero. Already when the second stage is most prominent at the lowest emission energy shown, the analyzing power remains essentially at zero over the whole angular range.

The common overall trend of a statistical multistep reaction mechanism, which drives pre-equilibrium reactions, is thus very evident in the angular- and emission energy distributions of the analyzing power. However, a difference depending on the the specific terminating steps which are available for (p,^{3}He) and (p,α) reactions also appears. The analyzing power of (p,^{3}He) reactions, without exception between incident energies of 100 and 160 MeV [12, 14–16], is found to be consistent with two-nucleon pickup as the terminating process at each individual stage of the reaction. On the other hand, (p,α) reactions appear to experience competition between pickup and knockout, with the magnitude of the two processes varying depending on details of the reaction process.

As shown in Figure 4, for the reaction ^{93}Nb(p,α) at an incident energy of 65 MeV and at an emission energy of 53 MeV, the shape of the analyzing power distribution is determined only by a knockout process. At an incident energy of 100 MeV, however, pickup clearly dominates [17, 19]. The strange trend over such a small change in incident energy for ^{93}Nb may be interpreted as an incident-energy dependent interplay between the magnitudes of the cross sec-

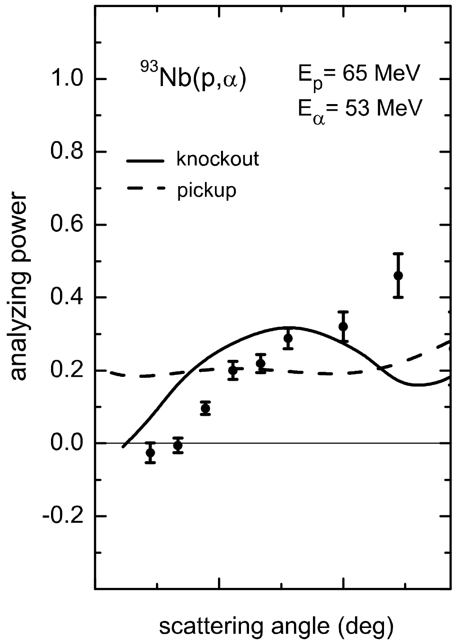

Figure 4. Analyzing power angular distributions for the reaction ^{93}Nb(p,α) at an incident energy of 65 MeV and at an emission energy of 53 MeV. The curves are predictions of the FKK theory. The solid curve is the prediction for α-particle knockout and the dished curve represents the result of a three-nucleon pickup mechanism in the final step leading to emission of the ejectile. Results are from Ref. [17].

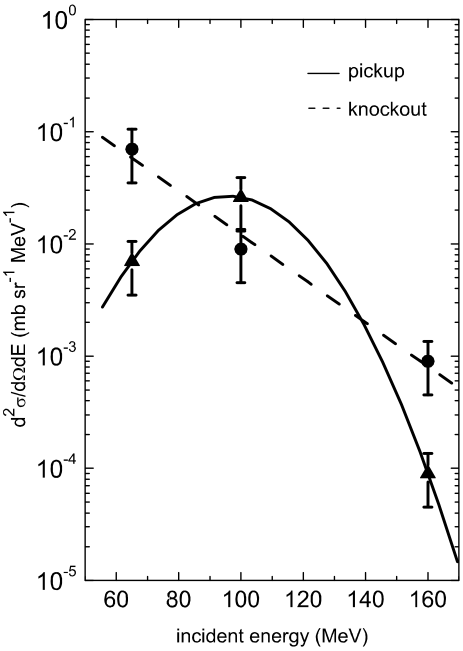

Figure 5. Incident energy dependencies of experimental cross sections extracted in Refs. [17–19] for the reaction ^{93}Nb(p,α). The emission energy is fixed at 20 MeV less than the incident energy. The component found for a knockout mechanism is shown as circles and a dashed line. The contribution of a pickup mechanism is indicated by triangles and a solid curve. The curves are arbitrary fits through the experimental values to guide the eye.

tions for the two competing processes. Absolute magnitudes are not only determined by α-cluster preformation probabilities and two-particle amplitudes, but also by the difference in linear momentum between the incident- and exit channels [19].

The trend of the two possible mechanisms, and the absolute cross section magnitude of each contributing to the ^{93}Nb(p,α) reaction at incident energies between 65 and 160 MeV, are displayed in Figure 5. Details of the methodology adopted for extraction of the relative magnitudes of the cross section contributions from the analysis of the experimental data are provided in Ref. [19]. The re-

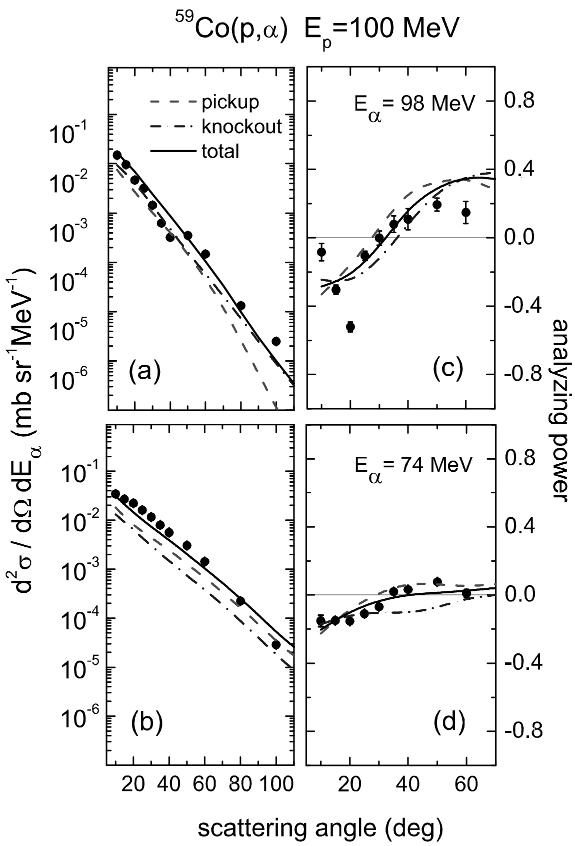

Figure 6. Cross section (a) – (b) and analyzing power (c) – (d) distributions for the reaction ^{59}Co(p,α) at an incident energy of 100 MeV. Emission energy for (a) is also as indicated in (c), and for (b) as also specified in (d). The curves correspond to FKK results for a terminating pickup mechanism (dashed curves), knockout (dashed-dot curves) or combined values (continuous curves). The displayed results are a subset selected from Ref. [19].

sult which was found for ^{93}Nb(p,α) implies that in general (p,α) pre-equilibrium reactions should display prominent differences in reaction mechanisms, depending amongst others on the structure details of the specific target nucleus which is investigated. This expectation appears to be supported by analyzing power angular distributions of ^{59}Co(p,α) at an incident energy of 100 MeV, shown in Figure 6. Whereas the predicted analyzing power is consistently too high for a pickup terminating process, it is always too low for knockout. With roughly equal cross section contributions from the two mechanisms, the predicted analyzing power gives better agreement with the experimental data.

For the target nucleus ^{93}Nb at the same incident energy, on the other hand, knockout contributes proportionally less [17] to the overall cross section. Although strictly not directly comparable, Figure 5 reveals that knockout contributes about 25% of the total (p,α) yield for ^{93}Nb, compared with 50% at forward scattering angles for ^{59}Co in Figure 6. This gives a rough indication of the trend with these two target masses.

Note that in the past it was assumed, because cross section angular distributions qualitatively change rather gradually with incident energy and target mass, effects due to structure of the nucleus would be suppressed due to the many stages involved in the statistical multistep reaction. Clearly analyzing power appears to contradict this expectation.

4 Summary and Conclusions

Insight into the reaction mechanism of proton-induced pre-equilibrium reactions provided by some of our recent published work was reviewed. Nucleon- and composite particle emission are clearly intimately-connected parts of the statistical multistep chain. At each stage of the interaction, emission of either a nucleon or some type of composite ejectile is possible. For (p,^{3}He) reactions, pickup of a nucleon pair as the terminating process from each stage of the pre-equilibrium chain is known to explain the appearance of cross section and analyzing power angular distributions at various emission energies and over a wide range of incident energies.

An interesting result is that (p,α) reactions appear to be driven by competition between pickup and knockout in the process leading to formation of the ejectile. Apart from the structure properties of the target nucleus, with inherent cluster preformation probability and three-nucleon amplitudes as crucial quantities that determine relative yields from the two processes, kinematic considerations would also apply. It was found that the inherent momentum mismatch between the incident and exit channels of (p,α) reactions, which increases with incident energy, affects a process driven by pickup differently from one in which knockout prevails.

Clearly the competing processes involved in (p,α) pre-equilibrium reactions should be studied further by investigating a larger range of target nuclei than the very few examples which have been investigated to date. The incident energy range between 100 and 200 MeV appears to be especially promising for future studies.

Acknowledgements

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