Proton induced pre–equilibrium reactions to the continuum as a test to the reaction mechanism

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Abstract

Pre-equilibrium proton induced emissions of light complex nuclei with energies in the continuum have been studied comprehensively for many years. The process is considered as an intra-nuclear nucleon-nucleon multistep statistical reaction with typical double-differential cross sections and especially analyzing power distributions. The final stage of the reaction may be a result of a direct pickup or knockout of the ejectile. The discussion on this subject continues to be a hot topic for theoretical and experimental investigations. Here we will discuss the interplay between the knockout and pickup mechanisms as final step of the pre-equilibrium reaction and its dependence on the energy of the projectile.

1 Introduction

Pre–equilibrium nuclear reactions have been studied extensively over many years. In the early nineties E. Gadioli and P.E. Hodgson collected all valuable experimental and theoretical results in a book [1] concluding that for a deeper insight into the reaction mechanism of this type of reaction a systematic study of their characteristics is needed. A comprehensive program for investigating the properties of the proton induced pre–equilibrium reactions to the continuum has been conducted in iThemba LABS in Faure, South Africa. The earliest results about the double differential cross–section of the ^{90}Zr(p, p') reaction [2] showed that the features of the experimental angular distributions can be reproduced very good by the statistical multistep direct theory of Feshbach, Kerman and Koonin (FKK) [3] (see Fig.1). First the classical exciton model of Griffin [4] exploits the idea that the projectile undergoes several intra-nuclear collisions before the final stage of the reaction. Quantum mechanical theories based on the same assumption were suggested also by Tamura, Udagawa and Lenske [5], Nishioka, Weidenmüller and Yoshida [6]. Later Koning and Akkermans [7] studied critically the models mentioned above and came to the conclusion that the calculated angular distribution of the ^{90}Zr(p, p') reaction at 80 MeV incident energy do not differ very strongly. Thus they recommended the simplest multistep direct method (the FKK model) as most adequate for the analysis of experimental data.

As part of the systematic studies [8–10] of proton induced pre–equilibrium reactions we have compare experimental data obtained in iThemba LABS with results from theoretical FKK calculations of (p, α) reactions to the continuum recognizing that the emission of composite particles follows the same multistep mechanism as the nucleon emission. In this contribution we will sketch briefly the method we use to study double–differential cross–section and analyzing power and discuss few examples which demonstrate the importance of the reaction mechanism as a crucial ingredient of the calculations.

2 The theoretical method

We assume that pre-equilibrium ($\vec{p}$,α) reactions occur in a series of nucleon–nucleon scattering events within the target, followed by a final process in which the α–particle is emitted. The single step direct reaction can be a knockout of an α–cluster or a pickup of a triton.

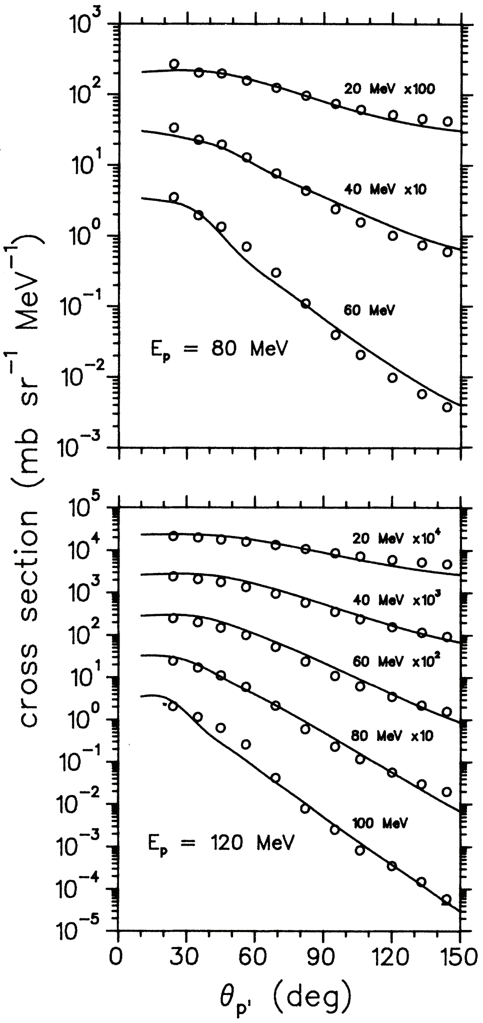

Fig. 1: Laboratory angle distribution for the reaction ^{90}Zr(p,p') at selected ejectile energies as adopted from Cowley et al. [2].

For the theoretical description of the $(\vec{p},\alpha)$ reaction we implement the FKK multistep direct theory [3], where the double differential cross section is a sum of terms related to one-, two- and so on steps.

$$\frac{d^2\sigma}{d\Omega dE} = \left(\frac{d^2\sigma}{d\Omega dE}\right)^{1-\text{step}} + \left(\frac{d^2\sigma}{d\Omega dE}\right)^{2-\text{step}} + \cdots . \tag{1}$$

The first-step cross section is calculated in terms of the DWBA method:

$$\left(\frac{d^2\sigma}{d\Omega dE}\right)^{1-\text{step}}_{(p,\alpha)} = \sum_{N,L,J} \frac{(2J+1)}{\Delta E}\frac{d\sigma^{\text{DW}}}{d\Omega}(\theta,N,L,J,E)\,, \tag{2}$$

where the differential cross sections $d\sigma^{\text{DW}}/d\Omega$ to particular final (N,L,J) states are calculated using the computational code DWUCK4 [11].

The distorted waves in the incident and outgoing channels are calculated within the hybrid nucleus-nucleus optical potential [12] for the volume part and standard spin-orbit potential, both ingredients of the optical potential being complex. The volume part generally depends on the radius–vector **r** connecting the centers of the target and projectile.

$$U(\mathbf{r}) \;=\; N^R V^{DF}(\mathbf{r}) \,+\, i N^I W^{DF}(\mathbf{r})\ . \tag{3}$$

The parameters N^R and N^I correct the strength of the microscopically calculated real V^{DF} and imaginary W^{DF} constituents of the whole potential.

The spin–orbit parts of the optical potentials can be chosen among the phenomenological potentials available in the literature, as we have done in [9, 10]. Another possibility is to use the standard form of the spin–orbit potential as defined in DWUCK4, but the depth and the geometrical parameters of the Woods–Saxon potential are those which fit best the double folding potential eq.3. This procedure reduces the number of the phenomenological parameters and derives all parts of the optical potentials in a consistent way.

When the emission energy decreases the multi–step contribution to the calculated observables have to be taken into account. Using the FKK theory [3] the two–step cross section is calculated as a convolution of the (p, p') cross section and the direct (p, α) cross section:

$$\left(\frac{d^2\sigma}{d\Omega dE}\right) \;=\; \int \frac{d\mathbf{k}}{(2\pi)^3}\left(\frac{d^2\sigma(\mathbf{k}_i,\mathbf{k})}{d\Omega_i dE_i}\right)_{(p,p')}\left(\frac{d^2\sigma(\mathbf{k},\mathbf{k}_f)}{d\Omega_f dE_f}\right)^{1-step}_{(p,\alpha)}\ , \tag{4}$$

where $\mathbf{k}_i,\ \mathbf{k}$ and $\mathbf{k}_f$ are the momenta of the initial, intermediate and final steps. The three-step double differential cross-section can be calculated analogously.

The theoretical (p, p') and (p, p', p'') double-differential cross section distributions which are required for the calculation of the two– and three–step contributions were derived from Refs. [8,13]. These cross section distributions which were extracted by means of a FKK theory, reproduce experimental inclusive (p, p') quantities [13]. Interpolations and extrapolations in incident energy and target mass were introduced to match the specific requirements accurately.

The extension of the FKK theory from cross–sections to analyzing power is formulated by Bonetti *et al.* [14]. The multistep expression for the analyzing power becomes

$$A_{\rm multistep} = \frac{A_1\left(\frac{d^2\sigma}{d\Omega dE}\right)^{1-\rm step} + A_2\left(\frac{d^2\sigma}{d\Omega dE}\right)^{2-\rm step} + \cdots}{\left(\frac{d^2\sigma}{d\Omega dE}\right)^{1-\rm step} + \left(\frac{d^2\sigma}{d\Omega dE}\right)^{2-\rm step} + \cdots}, \tag{5}$$

with A_i, $\{i = 1, 2, \ldots\}$ referring to analyzing powers for the successive multisteps.

One should emphasize the role of the analyzing power in the study of the reaction mechanism. The main advantage of the experiments with polarized proton beams is namely the possibility to measure this observable. The shape of the analyzing power as a function of the scattered angle is much more sensitive to the reaction mechanism then the differential cross–section. Moreover as the analyzing power is a ratio of cross–sections, it is independent of the absolute cross section of the reaction. For small difference between the incident and the outgoing energy, where the first step dominates, the analyzing power has a distinctive shape. When the higher steps take place, they affect significantly the shape and the magnitude of the analyzing power and it tents towards zero for low emission energies. Figs.3 and 2 illustrate this statement.

3 Energy dependence of the reaction mechanism

The mechanism of the direct $(\vec{p}, \alpha)$ reaction has been discussed intensively over the years, but a decisive conclusions has not been made. For example in Ref. [15] it was shown that calculations assuming pickup of a triton and knockout of an α–particle equally well fit the angular distribution and the analyzing power of the ^{90,92}Zr$(\vec{p}, \alpha)$ reactions to the ground state and the first few excited states, while the knockout mechanism is preferred for describing transitions to the continuum [16]. To address this problem for pre–equilibrium processes we studied proton induced reactions on ^{59}Co and ^{93}Nb at incident energies from 160 MeV to 65 MeV (see Ref. [17] and references there). We performed DWBA calculations assuming both reaction mechanisms and compared the theoretical results with the experimental data for the double differential cross–section and the analyzing power for a small difference between the incoming and outgoing energies, where the first–step process dominates. Numerically the difference between both types of calculations lies in the form factor, and the incoming and the outgoing distorted waves are calculated using the same optical model potentials for protons and α–particles, respectively.

In Ref. [9] was shown that at 160 MeV incident energy the experimental data for the characteristics of the ^{93}Nb(p, α) reaction are reasonably well described assuming that the ejectile originates from an α–cluster knockout in the final stage.

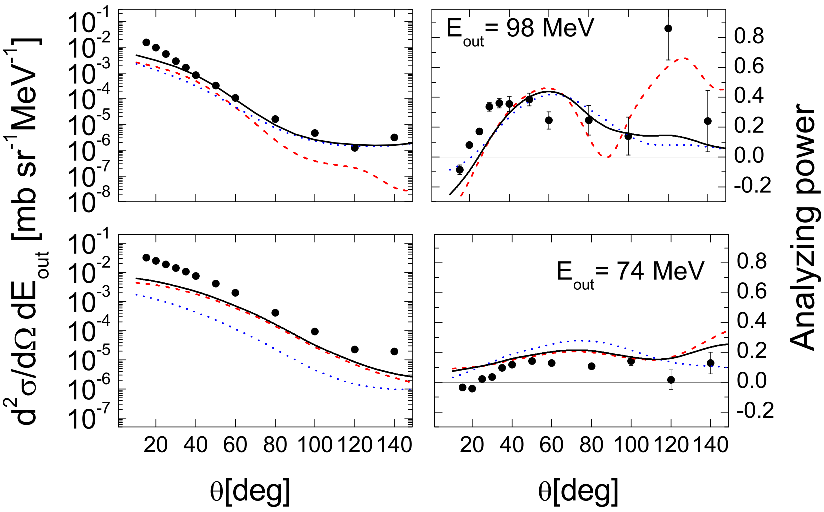

Fig. 2: Double-differential cross sections (left panels) and analyzing power (right panels) as a function of scattering angle θ for the ^{93}Nb$(\vec{p}, \alpha)$ reaction at an incident energy of 100 MeV and two α- particle emission energies E_{out} as indicated. Theoretical cross-section and analyzing power calculations for pickup (red dashed lines) and knockout (blue dashed-dotted lines) are shown, with the sums of both reaction mechanisms plotted as black solid lines.

In. Fig. 2 double-differential cross sections and analyzing power as a function of scattering angle for the ^{93}Nb$(\vec{p}, \alpha)$ reaction at an incident energy of 100 MeV and two α–particle emission energies E_{out} are shown. At the highest outgoing energy of 98 MeV where the first step contribution dominates the results for both reaction mechanisms, knockout and pickup, are shown. It is seen that for forward scattering angles the pickup differential cross–section is closer to the experimental points, while for the backwards angles the knockout process dominates. Looking at the analyzing power, the pickup is the reaction mechanism which describes best the main features of the shape and magnitude of the analyzing power. For the lower emission energies the knockout differential cross–section decreases faster then the pickup one. In this case we conclude that both reaction mechanisms should be taken into account although the importance of the pickup prevails.

To extend the study of the ^{93}Nb$(\vec{p}, \alpha)$ reaction for lower incident energies we re-examine the experimental data for 65 MeV proton incident energy by Sakai et al. [18]. We use the same procedure mentioned before. The double-differential cross–section and the analyzing power for the highest outgoing energy of 53 MeV are described reasonably well by the knockout mechanism and no other combination of pickup and knockout achieves better agreement with the experimental data. Once fitted at this emission energy the magnitudes of the differential cross section and the analyzing power are in very good agreement with the experimental data at lower emission energies as well.

The reason for the energy dependence of the reaction mechanism is in detail discussed in our

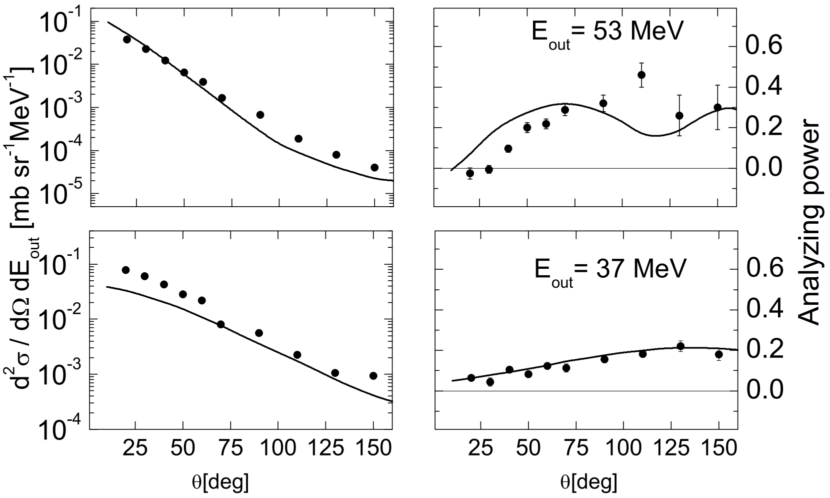

Fig. 3: Double-differential cross sections (left panels) and analyzing power (right panels) as a function of scattering angle θ for the ^{93}Nb$(\vec{p},\alpha)$ reaction at an incident energy of 65 MeV and two α- particle emission energies E_{out} as indicated. Theoretical calculations for a knockout reaction mechanism (solid line) are compared with the experimental data by Sakai et al. [18]

previous papers [17, 19]. The differential cross–section for either knockout or pickup depends on the difference between the angular momentum in the incident and exit channel, the so called momentum mismatch. Knockout is characterized by a low angular momentum relative to the core, because the α–particle is a fully paired system. Pickup in a (p,α) reaction involves a system of two neutrons and a proton and this composite system can have a large angular momentum in respect to the core. The momentum mismatch depends on the energy of the projectile, thus reaction mechanism is influenced strongly by the incident energy.

4 Conclusion

Based on the investigation of the pre–equilibrium ^{93}Nb$(\vec{p},\alpha)$ reaction we offer an explanation about the energy dependence of the reaction mechanism at the final step of the process. We have shown that both mechanisms - knockout and pickup are important and the angular momentum of the transferd composite particle to the rest of the system has a far-reaching consequence for the cross–section trends as a function of incident energy.

Acknowledgments

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