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Proton-Induced α-Particle Emission on ^{90}Zr at 72 MeV Incident Energy

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Abstract. The pre-equilibrium proton induced emission of light complex nuclei with energies in the continuum has been studied comprehensively for many years. Double-differential cross sections and especially analyzing power distributions are typical of an intranuclear nucleon-nucleon multistep statistical reaction mechanism. 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.

In this contribution results from the latest studies of the inclusive $(\vec{p}, \alpha)$ reaction at 72 MeV incident energy on ^{90}Zr to the continuum will be reported. The aim of the present investigation is to further develop the systematics of the dependence of the reaction mechanism on the target nucleus.

1 Introduction

In our previous studies we have considered in detail the dependence of the characteristics of the proton-induced pre-equilibrium reactions with emission of light particles to the continuum on the incident energy [1–4]. We have investigated ($\vec{p}$,^{3}He) and ($\vec{p}$,α) reactions on ^{59}Co and ^{93}Nb targets at proton energies from 65 to 160 MeV.

Double-differential cross section and analyzing power angular distributions were measured at various emission energies. The target nuclei were selected because they are naturally occurring mono-isotopic nuclides which are readily available and because earlier work suggests that the postulated reaction mechanism should not suffer from a drastic target-mass dependence.

The cross section and analyzing power angular distributions at a large range of emission energies are reproduced well by a statistical multistep pre-equilibrium theory, in which a combination of terminating knockout and pickup processes are major ingredients. The mix of mechanisms extracted from the theoretical analysis is valid for both target nuclei which shows that indeed the mass of the target does not influence the reaction mechanism.

In this contribution we report the results from the theoretical description of the inclusive $(\vec{p}, \alpha)$ reaction at 72 MeV incident energy on ^{90}Zr to the continuum within the statistical direct theory of Feshbach, Kerman and Koonin (FKK) [5]. The double-differential cross section and the analyzing power of the reaction will be compared to the experimental data published in [6]. We will be interested only in the case with the highest outgoing energy of 63 MeV reported because then the one step process dominates and the reaction mechanism can be clearly determined. The target nucleus ^{90}Zr is chosen because contrary to the targets studied before it is a double magic nucleus. We want to examine whether the structure of the target nucleus influences the mechanism of the pre-equilibrium reaction.

2 Calculations

The double differential cross section within the statistical multistep direct model [5] is a sum of terms related to one-, two- and so on steps.

In this report we will consider just the first step characteristics of the reaction. The first step double differential cross section is calculated in terms of the direct transfer reaction DWBA cross sections as expressed by Eq. (1)

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

where the differential cross sections $d\sigma^{\mathrm{DW}}/d\Omega$ to particular (N, L, J) states are calculated using the computational code DWUCK4 [7].

The distorted waves in the incident and outgoing channels are calculated using the hybrid nucleus-nucleus optical potential [8]. It has a real and an imaginary parts

$$U(\mathbf{r}) = N^R V^{DF}(\mathbf{r}) + iN^I W^{DF}(\mathbf{r}) + V_{SO}\ \mathbf{S.L} \quad , \qquad (2)$$

which generally depend on the radius-vector **r** connecting centers of the interacting nuclei. 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. In our studies of the ^{93}Nb(p,α) reaction [2, 3] the spin–orbit parts of the optical potentials were selected among the phenomenological potentials available in the literature. The calculations of the double differential cross section and the analyzing power of the ^{57}Co(p,α) reaction [4] demonstrated that one can successfully use the standard form of the spin-orbit potential as a derivative of the Woods-Saxon potential with geometrical parameters obtained by fitting the double folding potential Eq. (2). This procedure allows us to reduce the number of the phenomenological parameters and to construct all parts of the optical potentials in a consistent way

$$V_{SO}(\mathbf{r}) = N_{SO}^{R} V^{DF}(\mathbf{r}) + i N_{SO}^{I} W^{DF}(\mathbf{r}) \quad . \tag{3}$$

This procedure allows us to reduce the number of the phenomenological parameters and to construct all parts of the optical potentials in a consistent way.

In our previous studies [1–3, 9] we have intensively discussed the importance of the reaction mechanism for the correct theoretical description of the pre-equilibrium reactions induced by polarized protons. It was shown that, depending on the incident energy, the pickup and knockout mechanisms play different roles. Although a previous study by Bonetti et. al [10] of the reaction ^{58}Ni($\vec{p}$,α) at 72 MeV incident energy indicates a dominance of knockout, we will allow a mix of pickup and knockout for the description of the double differential cross-section and analyzing power of the ^{90}Zr($\vec{p}$,α) reaction at the same proton energy.

3 Results

Theoretical calculations for pickup, knockout and a combination of both mechanisms are compared in Figure 1 with the experimental data [6] for the ^{90}Zr($\vec{p}$,α) reaction at 72 MeV proton incident energy and 63 MeV α-particle outgoing energy.

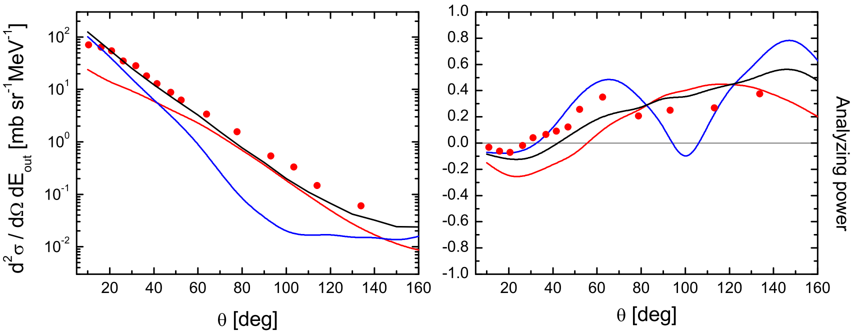

Figure 1. Double-differential cross sections and analyzing power as a function of scattering angle θ for the ^{90}Zr($\vec{p}$,α) reaction at an incident energy of 72 MeV and 63 MeV outgoing energy. Theoretical cross section calculations for pickup (blue line) and knockout (red line) are shown, with the sum of both reaction mechanisms plotted as continuous black curves. The experimental data [6] are shown by dots.

The scaling parameters of the double folding potentials are determined by fitting the total differential cross-section and the analyzing power for the highest available outgoing energy of 63 MeV. We assume that just the direct emission takes place and the double differential cross section is expressed by Eq. (1). The values of the parameters which reproduce best the experimental data are listed in Table 1 .

Table 1. Values of scaling parameters N^R and N^I in Eq. (2) and N^R_{SO} and N^I_{SO} in Eq. (3) for the incident and outgoing channels

	N^R	N^I	N^R_{SO}	N^I_{SO}
incident channel	1.0	1.0	1.5	0.0
outgoing channel	1.0	1.3	0.0	0.0

Let us consider in details the contribution of both reaction mechanisms. It is seen that the theoretical double-differential cross sections have rather different shapes for a knockout or pickup reaction mechanism. The pickup cross section alone fits the forward angles, while the knockout cross section reproduces the experimental data very well at larger angles. The sum of the cross sections originating from both reaction mechanisms is required for a reasonably good fit to the complete set of experimental data over the whole range of scattering angles. The same conclusion is valid for contributions from both reaction mechanisms to the analyzing power.

4 Conclusion

The aim of this study was to see whether the structure of the target nucleus influences the reaction mechanism of the pre-equilibrium ($\vec{p}$,α) reaction to the continuum. We see that in the case of the double magic target ^{90}Zr the interplay of both mechanisms, pickup and knockout, ensures good reproduction of the experimental data. The same conclusion is true in the case of the ^{93}Nb($\vec{p}$,α) reaction, but at higher incident energy. We can not make a definite conclusion on the importance of the nuclear structure of the target yet, but there are experimental data of the double differential cross section and analyzing power for some other nuclei as targets in proton induced pre-equilibrium reactions at 72 MeV incident energy reported in [6]. The further investigation of the role of both reaction mechanisms in those cases will be very interesting.

Acknowledgments

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