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^{59}Co($\vec{p}, \alpha$) reaction at 100 MeV incident energy – statistical multistep direct reaction into the continuum of outgoing energies

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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 both theoretical and experimental investigations. In this paper the results from the latest studies of the inclusive ($\vec{p}$,α) reactions on ^{59}Co to the continuum will be reported. The formalism based on the statistical multistep direct emission formulation of Feshbach, Kerman and Koonin is found to give a reasonably good reproduction of cross section and analyzing power distributions at various emission energies. Special attention will be paid to the details of the calculations.

1 Introduction

For many years pre-equilibrium reactions have been an interesting topic of both experimental and theoretical studies. It has been shown that the reaction mechanism can be understood fairly accurately in terms of a series of multiple intranuclear nucleon-nucleon collisions, which finally end in a direct transfer of the emitted particle [1, 2]. The reaction mechanism of the direct transfer depends on the incident energy of the projectile and on the ejectile.

In our recent papers [3–5] we have investigated the properties of the ^{93}Nb($\vec{p}$,α) reactions at 65 MeV to 160 MeV incident energy to the continuum, especially the dependence of the reaction mechanism on the proton energy. In this paper we will test the A–dependence of properties of the pre–equilibrium reactions in the lower mass region. We will study the properties of the ^{59}Co($\vec{p}$,α) reaction at 100 MeV incident energy for a number of outgoing energies. The scheme developed for the study of ^{93}Nb($\vec{p}$,α) reaction to the continuum will be followed.

We mention briefly the basics of the experimental procedure and theoretical study in Sec. 2. Results are discussed in Sec. 3 and conclusions are drawn in Sec. 4.

2 Experiment and theory

The experiment has been performed at iThemba LABS in Faure, South Africa. The double differential cross-section and analyzing power as a function of scattering angle for the ^{59}Co($\vec{p}$,α) reaction at 100 MeV incident energy of the polarized proton beam and for different outgoing energies of the ejectile have been measured during the same period as the previous experiment on ^{93}Nb. Details of the experimental technique were presented in Ref. [4].

We describe the ($\vec{p}$,α) inclusive reactions at incident energy of 100 MeV as a pre-equilibrium reaction. We assume that this type of reaction occurs 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.

For the theoretical description of the (p, α) reaction we implement the multistep direct theory of Feshbach, Kerman and Koonin (FKK) [6].

The double differential cross section is a sum of terms related to one-, two- and so on steps.

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

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

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

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 [7].

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To calculate the distorted waves in the incident and outgoing channels we use the hybrid nucleus-nucleus optical potential [8] 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 $\mathbf{r}$ connecting the centers of the target and projectile

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

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. In the studies of the ^{93}Nb(p,α) reaction [3–5] we selected the spin–orbit parts of the optical potentials among the phenomenological potentials available in the literature. In this set of calculations we 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 allows us to reduce the number of the phenomenological parameters and to construct all parts of the optical potentials in a consistent way.

The parameters of the double folding potentials N^R and N^I are determined by fitting the differential cross-section and the analyzing power for the highest outgoing energy, E_{out}=98 MeV in this case, where just the direct emission takes place. The values of the parameters which reproduce best the experimental data are N^R=0.5 and N^I=0.08 for the proton–nucleus potential and N^R=1.0 and N^I=1.0 for the outgoing channel. The values of the scaling factors are kept unchanged for the rest of the calculations at other outgoing energies.

When the emission energy decreases the multi–step contribution to the calculated observables have to be taken into account. Using the FKK theory [6] the two–step cross section is calculated as a convolution of the (p, p') cross section and the direct (p, α) cross section:

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

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. [9, 10]. These cross section distributions which were extracted by means of a FKK multistep direct reaction theory, reproduce experimental inclusive (p, p') quantities [9]. Interpolations and extrapolations in incident energy and target mass were introduced to match the specific requirements accurately.

In previous work [3], intermediate steps which involve neutrons, such as (p, n, α), were not explicitly taken into account because we assumed that different nucleons may be treated on an equal footing in the multistep part of the reaction. This meant that a simple renormalization of the (p, p') and (p, p', p'') cross sections should be introduced to correct for the influence of the intermediate counterparts which involve neutrons. In the present calculations we take into account explicitly the (p, n, α) process by assuming that $d^2\sigma^{(p,n)}/d\Omega dE = d^2\sigma^{(p,p')}/d\Omega dE$ and also the four possible combinations of two–step intranuclear collisions (p, x, x), $x = n, p$ with $d^2\sigma^{(p,x,x)}/d\Omega dE = d^2\sigma^{(p,p',p'')}/d\Omega dE$.

The extension of the FKK theory from cross sections to analyzing power is formulated by Bonetti *et al.* [11]. The multistep expression for the analyzing power becomes

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

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

The mechanism of the direct (p, α) reaction has been discussed intensively over the years but a decisive conclusions has not been made. In our previous paper [4] we concluded that the reaction mechanism in the ^{93}Nb($\vec{p}, \alpha$) reaction changes from a dominant knockout process at 65 MeV incident energy, to a combination of pickup and knockout participating at 100 MeV, and then back to only knockout being important at 160 MeV.

We anticipate that for the ^{59}Co($\vec{p}, \alpha$) reaction at 100 MeV incident energy both reaction mechanisms should play an important role for the adequate theoretical description of the double–differential cross section and analyzing power at different outgoing energies.

3 Results

The results from the experiments and theoretical studies of the ^{59}Co($\vec{p}, \alpha$) at 100 MeV incident energy are available for outgoing energies starting from 98 MeV (with 103 MeV as a kinematic limit due to a positive Q-value of the reaction of 3.24 MeV) down to 34 MeV. In this paper we discuss the results for some outgoing energies which are representative for the contribution of the pickup and knockout reaction mechanisms to the total differential cross section and analyzing power.

First of all we will consider the E_{out}=98 MeV reaction. We assume that both reaction mechanisms contribute to the direct process and the multi-step processes are negligible. As it is seen in Fig. 1 the theoretical double-differential cross sections have rather different shapes and only the sum of them reproduce the complete set of experimental data over the whole range of scattering angles.

The theory predicts that the relative contribution of the one–step reaction decreases as the emission energy drops, with higher steps becoming progressively more important towards lower emission energy. This is a general feature of multistep calculations, as was also found in our previous work [12–14]. Although the actual step which is dominant at a specific emission energy only influences the shape of

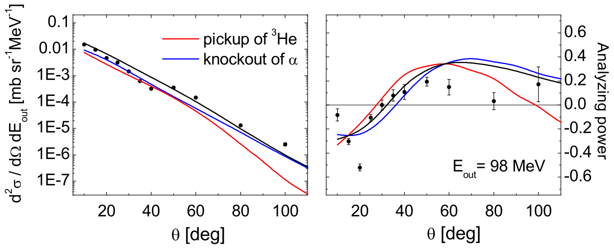

Figure 1. (Color online) Double-differential cross section and analyzing power as a function of scattering angle θ for the ^{59}Co(p,α) reaction at an incident energy of 100 MeV and α–particle outgoing energy E_{out}=98 MeV. Theoretical cross section and analyzing power calculations assuming pickup reaction mechanism (red curves) and knockout (blue curves) are presented.

the cross section relatively slightly, an appreciable contribution of higher steps affects the analyzing power distribution profoundly.

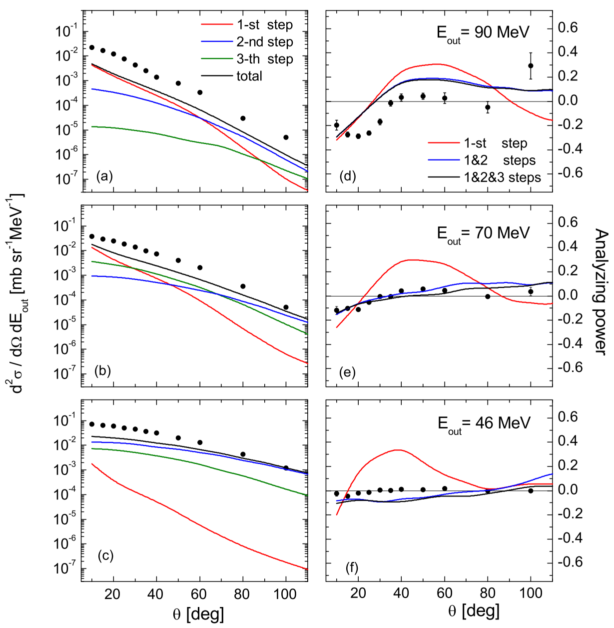

Figure 2. (Color online) Double-differential cross section and analyzing power as a function of scattering angle θ for the ^{59}Co$(\vec{p},\alpha)$ reaction at an incident energy of 100 MeV and various α-particle emission energies $E_{\rm out}$ as indicated. Theoretical cross section calculations for one– (red), two– (blue) and three–step (green) are shown. The sums of the contributions is plotted in black. The experimental analyzing power distributions are compared with theoretical calculations for a one–step reaction (red), one– plus two–step reaction (blue), and one– plus two– plus three–step reaction (black).

In Fig. 2, we illustrate the contribution of the one– , two– and three–step processes to the differential cross section and analyzing power for three outgoing energies, where all three multistep processes influence the shape and magnitude of both observables to a large extent. The experimental data for the double-differential cross sections and analyzing power are compared with the theoretical cross section calculations assuming a pickup reaction mechanism for one–, two– and three– step processes. It is seen that at the highest outgoing energy the one–step contribution is significant just for the forward angles while the two– and three– step processes determine entirely the magnitude of the rest of the double differential cross section. The role of the direct process to the analyzing power is to determine the shape of the distribution but the higher steps smooth the distribution and decrease its magnitude.

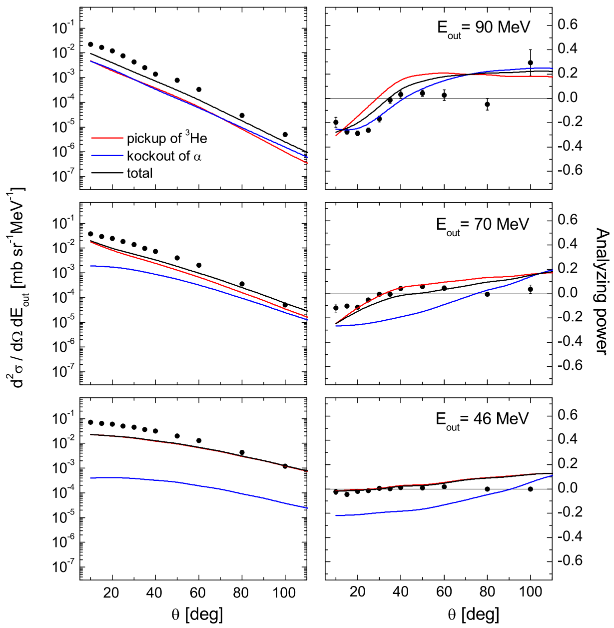

Figure 3. (Color online) Double-differential cross sections and analyzing power as a function of scattering angle θ for the ^{59}Co$(\vec{p},\alpha)$ reaction at an incident energy of 100 MeV and various α-particle emission energies $E_{\rm out}$ as indicated. Theoretical cross section calculations for pickup (red) and knockout (blue) are shown, with the sums of both reaction mechanisms plotted in black. The experimental analyzing power distributions are compared with theoretical calculations for pickup (red), knockout (blue) and the sum of both reaction mechanisms (black lines).

In Fig. 3, we plot the multistep double differential cross section and analyzing power assuming pickup and knockout at three values of the outgoing energies. It is seen that the sum of the contributions of both reaction follows the shape of the experimental distributions at the highest emission energy of 90 MeV. The differential cross sections of the knockout reaction mechanism decrease faster than those for pickup towards lower emission energies. Therefore, on average the total differential cross section is dominated by the pickup contribution at an incident energy of 100 MeV.

Results for the analyzing power are also very interesting. For higher outgoing energies the interplay of pickup and knockout reaction mechanisms accurately reproduces the experimental data. For example, for $E_{\rm out}$=90 MeV and $E_{\rm out}$=70 MeV neither mechanism alone reproduces the behavior of the experimental analyzing power well at backward angles. Furthermore, as for the lowest α-particle emission energy the magnitude of the analyzing power data decreases and at 46 MeV the analyzing power of the ^{59}Co(p, α) reaction is essentially zero from the experiment, in agreement with the theoretical prediction.

4 Conclusion

The present experimental and theoretical studies of the ^{59}Co$(\vec{p}, \alpha)$ reaction at 100 MeV confirm the conclusions made previously for the heavier target ^{93}Nb that the reaction mechanism is a combination of pickup and knockout. The contribution of pickup increases smoothly, starting from the highest outgoing energy until at low emission energies it totally dominates the differential cross section and analyzing power. The explicit account of the two– and three– step processes which involve intermediate neutron scattering significantly improves the reproduction of the experimental data at low outgoing energies by the FKK calculations.

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References

[1] E. Gadioli and P.E. Hodgson, *Pre-Equilibrium Nuclear Reactions* (Oxford University Press, New York, 1991)

[2] A.J. Koning and M.C. Duijvestijn, Nucl. Phys. A **744**, 1576 (2004)

[3] S.S. Dimitrova, A.A. Cowley, J.J. van Zyl, E.V. Zemlyanaya, and K.V. Lukyanov, Phys. Rev. C **89**, 034616 (2014)

[4] S.S. Dimitrova, A.A. Cowley, E.V. Zemlyanaya, and K.V. Lukyanov, Phys. Rev. C **90**, 054604 (2014)

[5] S.S. Dimitrova, A.A. Cowley, E.V. Zemlyanaya, and K.V. Lukyanov, *Proc. 33nd Int. Workshop on Nuclear Theory* (Rila, Bulgaria, June 22-28, 2014), eds. A. Georgieva, N. Minkov, Heron Press, Sofia, p.106, ISSN: 1313-2822

[6] H. Feshbach, A. Kerman and S. Koonin, Ann. Phys. (N. Y.) **125**, 429 (1980)

[7] P.D. Kunz and E. Rost, *Computational Nuclear Physics*, eds. K. Langanke *et al*. (Springer-Verlag, Berlin, 1993) Vol. 2, Chap. 5.

[8] V.K. Lukyanov, E.V. Zemlyanaya, and K.V. Lukyanov, JINR Preprint P4-2004-115, JINR, Dubna, 2004; Phys. At. Nucl. **69**, 240 (2006)

[9] W.A. Richter, A.A. Cowley, G.C. Hillhouse, J.A. Stander, J.W. Koen, S.W. Steyn, R. Lindsay, R.E. Julies, J.J. Lawrie, J.V. Pilcher, and P.E. Hodgson, Phys. Rev. C **49**, 1001 (1994)

[10] A.A. Cowley, G.J. Arendse, J.W. Koen, W.A. Richter, J.A. Stander, G.F. Steyn, P. Demetriou, P.E. Hodgson, and Y. Watanabe, Phys. Rev. C **54**, 778 (1996)

[11] R. Bonetti, L. Colli Milazzo, I. Doda, and P.E. Hodgson, Phys. Rev. C **26**, 2417 (1982)

[12] A.A. Cowley, G.F. Steyn, S.S. Dimitrova, P.E. Hodgson, G.J. Arendse, S.V. Förtsch, G.C. Hillhouse, J.J. Lawrie, R. Neveling, W.A. Richter, J.A. Stander, and S. M. Wyngaardt, Phys. Rev. C **62**, 064605 (2000)

[13] A.A. Cowley, J. Bezuidenhout, S.S. Dimitrova, P.E. Hodgson, S.V. Förtsch, G.C. Hillhouse, N.M. Jacobs, R. Neveling, F.D. Smit, J.A. Stander, G.F. Steyn, and J.J. van Zyl, Phys. Rev. C **75**, 054617 (2007)

[14] A.A. Cowley, J.J. van Zyl, S.S. Dimitrova, E.V. Zemlyanaya, and K.V. Lukyanov, Phys. Rev. C **85**, 054622 (2012)