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Proton-Induced α-Particle Emission into the Continuum of Outgoing Energies

S.S. Dimitrova[1], **A.A. Cowley**[2,3]

[1]Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, 1784 Sofia, Bulgaria
[2]Department of Physics, Stellenbosch University, Private Bag X1, Matieland, 7602, South Africa
[3]iThemba Laboratory for Accelerator Based Sciences, P O Box 722, Somerset West 7129, South Africa

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 we will report results about the cross section and analyzing power distributions for the ^{93}Nb($\vec{p}$,α) reactions at 100 MeV incident energy to the continuum. A 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. The contribution of the pickup and knockout reaction mechanism for various proton energies is discussed in detail.

1 Introduction

This contribution may be considered as a supplement to the paper [1], since it contains results about the cross section and analyzing power distributions for the ^{93}Nb($\vec{p}$,α) reactions at 100 MeV incident energy and additional outgoing energies, not reported there.

The pre-equilibrium reactions have been explored both experimentally and theoretically for many years [2–4]. 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. The reaction mechanism of the direct transfer depends on the incident energy of the projectile and on the ejectile. For example the double-differential cross section and analyzing power of proton-induced emission of ^{3}He into the continuum in the incident energy range below 200 MeV is consistent [5–7] with a simple two-nucleon pickup process convoluted with (p, p') and

(p, p', p'') cross sections within the statistical multistep direct emission model of Feshbach, Kerman and Koonin [9].

In our recent papers [1,8] we have investigated the properties of the ^{93}Nb($\vec{p}$,α) reactions at 160 MeV to 65 MeV incident energy to the continuum, especially the dependence of the reaction mechanism on the proton energy. It was shown that the 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. Here we will complete the systematics of outgoing energies for the ^{93}Nb($\vec{p}$,α) reaction at 100 MeV incident energy. This will confirm the conclusion that the reaction mechanism of the direct transfer at 100 MeV incident energy is a combination of pickup and knockout.

We will sketch briefly the experimental procedure in Sec. II and the theoretical formulation of our study in Sec. III. The comparison of the experimental and theoretical results is discussed in Sec. IV.

2 Experiment

The reaction ^{93}Nb($\vec{p}$,α) at an incident energy of 100 ± 0.5 MeV was measured at iThemba LABS in Faure, South Africa. A description of the facility is available in Ref. [10].

Two detector telescopes, each consisting of a 500-μm silicon surface-barrier detector followed by a NaI(Tℓ) crystal coupled to a phototube, were positioned at symmetric angles on opposite sides of the incident beam in a 1.5-m diameter scattering chamber. The telescopes were collimated to a solid angle acceptance of about 1.1 msr. The scattering-angle positions were set to an accuracy of better than 0.2° with respect to the incident beam.

Two self-supporting targets of naturally occurring niobium (100% in the isotope ^{93}Nb) of thicknesses of approximately 1 and 5 mg/cm^2 were used. The main systematic uncertainty in the cross section data – about 8% – originates from the absolute value of the target thickness and its uniformity.

The incident proton beam was polarized to a nominal value of 80% perpendicular to the reaction plane, and the direction of the polarization was switched at 5-s intervals during measurements. Variation between the degree of polarization for the two directions was less than 10%. These values were monitored regularly by means of elastic scattering of the proton beam from a carbon target at a scattering angle where the analyzing power is large and known accurately.

The use of detector telescopes positioned symmetrically with respect to the incident proton beam, together with the switching of the polarization direction allows us to minimize systematic errors in the analyzing power measurements. The vector analyzing power is calculated from the expression [11], which follows from the standard Basel-Madison conventions, as

$$A_y = \frac{L - R}{P(L + R)}, \tag{1}$$

with

$$L = \sqrt{L_u R_d}, \tag{2}$$

and

$$R = \sqrt{L_d R_u}. \tag{3}$$

The average polarization of the beam is P. The summed counts in each detector for a given energy interval in the spectra are indicated by L (left) or R (right), with subscripts which indicate the spin direction of the projectile as either up (u) or down (d). The convention is as defined by a spectator facing along the momentum direction of the incident beam upstream from the target.

3 Calculations

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 intranuclear N-N steps preceding 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. We will consider the contribution of both reaction mechanisms to the total double-differential cross section and analyzing power for different energies of the α particle in the outgoing channel.

The theory applied to the (p, α) reaction is based on the multistep direct theory of Feshbach, Kerman and Koonin (FKK) [9]. The details of the calculations of the characteristics of the ^{93}Nb($\vec{p}$,α) reaction at an incident energy of 100 MeV are described in Ref. [1], thus now we will just briefly outline the main expressions.

The double differential cross section within the statistical multistep direct model [9] is a sum of terms related to one-, two- and so on steps.

$$\frac{d^2\sigma}{d\Omega dE} = \left(\frac{d^2\sigma}{d\Omega dE}\right)^{1-\mathrm{step}} + \left(\frac{d^2\sigma}{d\Omega dE}\right)^{2-\mathrm{step}} + \cdots , \tag{4}$$

The first-step cross section is the cross-section of the direct transfer reaction calculated in terms of the DWBA:

$$\left(\frac{d^2\sigma}{d\Omega dE}\right)^{1-\mathrm{step}}_{(p,\alpha)} = \sum_{N,L,J} \frac{(2J+1)}{\Delta E} \frac{d\sigma^{\mathrm{DW}}}{d\Omega}(\theta, N, L, J, E) , \tag{5}$$

where the differential cross sections $d\sigma^{\mathrm{DW}}/d\Omega$ to particular (N, L, J) states are calculated using the computational code DWUCK4 [12].

As in the previous studies we use the hybrid nucleus-nucleus optical potential [16] in the incident and outgoing channels. It has real and imaginary parts:

$$U(\mathbf{r}) \;=\; N^R V^{DF}(\mathbf{r}) \;+\; iN^I W(\mathbf{r}), \tag{6}$$

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 constituents of the whole potential. In our calculations their values for the proton-nucleus potential are equal to unity. Very good agreement with the experimental data for the highest emission energy E_{out}=98 MeV can be obtained if the values of N^R and N^I for the exit channel are kept equal to unity as well. For the rest of the outgoing energies we used the values N^R=1 and N^I=2.

The second-step cross section is calculated as a convolution of the (p, p') cross section and the direct (p, α) cross section:

$$\left(\frac{d^2\sigma}{d\Omega dE}\right)^{2-step} = \int \frac{d\mathbf{k}}{(2\pi)^3} \left(\frac{d^2\sigma(\mathbf{k}_i, \mathbf{k})}{d\Omega_i dE_i}\right)_{(p,p')} \left(\frac{d^2\sigma(\mathbf{k}, \mathbf{k}_f)}{d\Omega_f dE_f}\right)^{1-step}_{(p,\alpha)} , \quad (7)$$

where $\mathbf{k}_i$, $\mathbf{k}$ and $\mathbf{k}_f$ are the momenta of the initial, the intermediate and final steps. Analogously we calculate the third-step double differential cross-section as well.

The theoretical (p, p') and (p, p', p'') double-differential cross section distributions which are required to calculate the contributions of the second- and third-step processes were derived from Refs. [13, 14]. These cross section distributions were extracted by means of a FKK multistep direct reaction theory, which reproduce experimental inclusive (p, p') quantities [13] on target nuclei which are close to those needed for this work, and in an appropriate incident energy range. Interpolations and extrapolations in incident energy and target mass were introduced to match the specific requirements accurately.

In previous work [8], 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 these 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 Ferman-Feshbach-Koonin theory from cross sections to analyzing power is described by Bonetti *et al.* [15]. The multistep expression for the analyzing power becomes

$$A_{\text{multistep}} = \frac{A_1 \left(\frac{d^2\sigma}{d\Omega dE}\right)^{1-\text{step}} + A_2 \left(\frac{d^2\sigma}{d\Omega dE}\right)^{2-\text{step}} + \cdots}{\left(\frac{d^2\sigma}{d\Omega dE}\right)^{1-\text{step}} + \left(\frac{d^2\sigma}{d\Omega dE}\right)^{2-\text{step}} + \cdots}, \quad (8)$$

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 [1] we made the conclusion that the reaction mechanism in the ^{93}Nb($\vec{p}$,α) 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. The theoretical double-differential cross sections have rather different shapes for a knockout or pickup reaction mechanism. Whereas the pickup cross section can be scaled to fit the forward angles, 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 good fit to the complete set of experimental data over the whole range of scattering angles. The scaling factors, which are needed to fit the experimental differential cross sections at 98 MeV emission energy, the highest value of the kinematically allowed outgoing energy, where only the direct transfer takes place, are kept unchanged for the rest of the calculations at other outgoing energies.

4 Results

The results from the experiments and the theoretical studies of the ^{93}Nb($\vec{p}$,α) at 100 MeV incident energy are available for outgoing energies starting from 98 MeV (with 106 MeV as a kinematic limit due to a positive Q-value of the reaction of 6.4 MeV) down to 34 MeV. In [1] we have chosen the ones which are representative of the contribution of both reaction mechanisms to the total differential cross section and analyzing power, including the highest and the lowest outgoing energies. Here we will show some complementary examples.

First of all we will illustrate the contribution of the one-, two and three-step processes to the differential cross section and the analyzing power for 78 MeV outgoing energy, where all three multistep processes form the shape and the magnitude of the differential cross section and the analyzing power at the same extend.

The theory predicts that the relative contribution of the first-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 [5–7]. Although the actual step which is dominant at a specific emission energy only influences the shape of the cross section relatively slightly, an appreciable contribution of higher steps affects the analyzing power distribution profoundly.

In Figure 1 the experimental data for the double-differential cross sections and analyzing power for the ^{93}Nb(p,α) reaction at an incident energy of 100 MeV and α–particle outgoing energy E$_{out}$=78 MeV are compared with the theoretical cross section calculations assuming pickup reaction mechanism for one, two and three steps. We have chosen the pickup reaction mechanism because it dominates for this incident energy [1]. It is seen that at 30 MeV below the upper

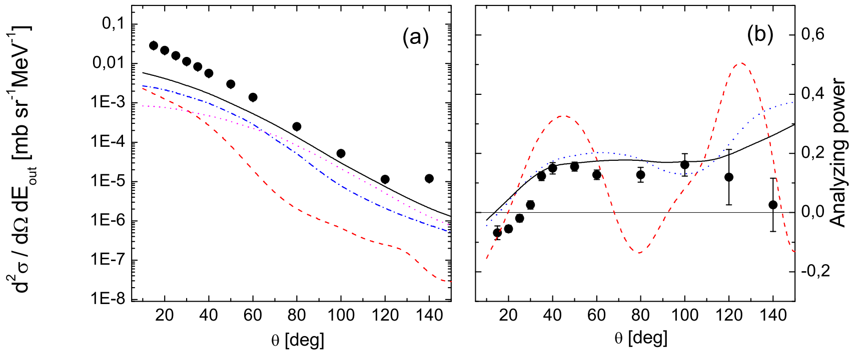

Figure 1. Double-differential cross sections (a) and analyzing power (b) as a function of scattering angle θ for the ^{93}Nb(p,α) reaction at an incident energy of 100 MeV and α–particle outgoing energy E_{out}=78 MeV. Theoretical cross section calculations assuming pickup reaction mechanism for one step (— — —) two steps (·····) and three steps (—·—·—) are shown, with the sums of the contributions plotted as continuous curves.

kinematical limit of the 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.

As mentioned before the aim of this paper is to test the conclusions about the role of the reaction mechanism of the ^{93}Nb(p,α) reaction at 100 MeV incident energy for different outgoing energies. In Figure 2 we plot the multistep double differential cross section and the analyzing power assuming pickup and knock out at five values of the outgoing energies ranging from 98 to 38 MeV. 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 98 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 lower outgoing energies the magnitude of the analyzing power data decreases and the interplay of pickup and knockout reaction mechanisms accurately reproduces the experimental data. For example in panel (g) neither mechanism alone reproduces the behavior of the experimental analyzing power well at backward angles.

Furthermore, as for the lowest α-particle emission energy [1], at 38 MeV the analyzing power of the ^{93}Nb(p,α) reaction is essentially zero from the experiment, in agreement with the theoretical prediction.

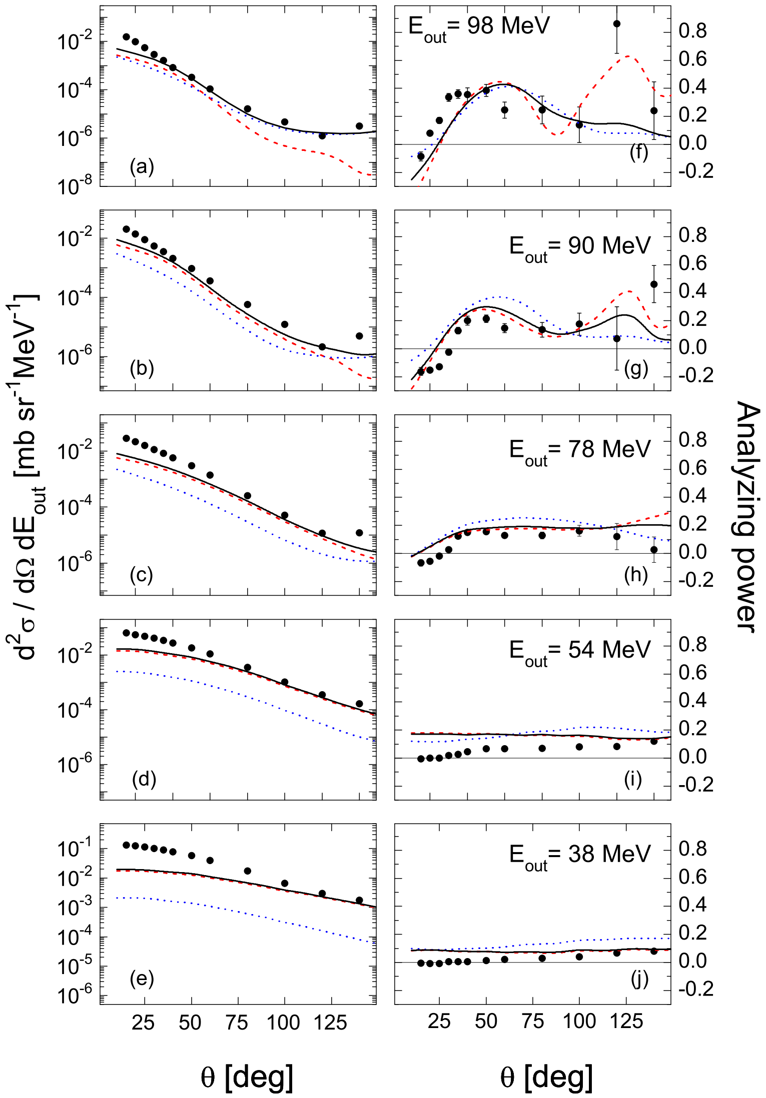

Figure 2. Double-differential cross sections (a)-(e) and analyzing power (f)-(j) as a function of scattering angle θ for the ^{93}Nb(p,α) reaction at an incident energy of 100 MeV and various α-particle emission energies $E_{\rm out}$ as indicated. Theoretical cross section calculations for pickup (— — —) and knockout (· · ·) are shown, with the sums of both reaction mechanisms plotted as continuous curves. The experimental analyzing power distributions are compared with theoretical calculations for pickup (— — —), knockout (· · ·) and the sum of both reaction mechanisms (solid lines).

5 Conclusion

The reaction mechanism in the ^{93}Nb($\vec{p}$,α) reaction at 100 MeV is a combination of pickup and knock out. 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.

The usual assumption is that a target such as ^{93}Nb is representative of nuclei in general as far as the pre-equilibrium (p,α) reaction is concerned. However, the present conclusion regarding the change in the ratio of participating mechanisms for this target needs to be confirmed for other nuclear species.

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