Multistep direct reaction analysis of analyzing powers of continuum spectra in (p,α) reactions

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The multistep direct reaction method, applied earlier to fit successfully the continuum spectra of (p,α) reactions, is shown to explain also their analyzing powers very well.

[NUCLEAR REACTIONS ^{93}Nb($\vec{p}$, α), E_p=65 MeV, multistep direct reaction theory analysis of the spectrum and the analyzing power.]

Recently, we succeeded in fitting[1-3] a few examples of continuum cross sections observed in light-ion induced reactions. A multistep direct reaction (MSDR) method was used. It is a challenging problem to see whether our method describes as well more intriguing features of the reaction, e.g., the analyzing powers (A_y). The A_y's were, in fact, measured recently by Sakai *et al.*,[4] with surprisingly large values. The purpose of the present article is to show that our MSDR method does fit nicely these new data as well.

The data of Sakai *et al.*[4] include those of $(\vec{p},p')$, $(\vec{p},d)$, and $(\vec{p},\alpha)$ reactions with several targets, but a fixed proton energy of E_p=65 MeV. For simplicity of the presentation, we shall restrict ourselves here to the ^{93}Nb$(\vec{p},\alpha)$ data. Previously,[2] we fit successfully the continuum spectra[5] of the ^{54}Fe(p,α) reaction, taken with E_p=62 MeV, very close to the E_p value used by Sakai *et al.*[4] It can be anticipated that our previous experience,[2] that it was necessary and sufficient to take into account contributions of one- and two-step processes, is repeated here.

The one-step process to be considered is just the (p,α) pickup, creating a three-hole (3h) state. As for the two-step processes, we may consider as dominant ones the (p,α',α) and (p,p',α) processes, both of which involve an inelastic-scattering step, creating a particle-hole (ph) pair.

Since we intend to calculate the A_y in the present work, we must calculate first the left (σ_L) and the right (σ_R) cross sections, both being contributed from the above mentioned processes. The expression of the theoretical A_y we are to calculate may thus be given as

$$A_y(E_\alpha,\theta)=[\sigma_L(E_\alpha,\theta)-\sigma_R(E_\alpha,\theta)]/[\sigma_L(E_\alpha,\theta)+\sigma_R(E_\alpha,\theta)]\,. \tag{1}$$

Here, for example,

$$\sigma_R(E_\alpha,\theta)=\sigma_R^{(p\alpha)}(E_\alpha,\theta)+\sigma_R^{(p\alpha\alpha)}(E_\alpha,\theta)+\sigma_R^{(pp\alpha)}(E_\alpha,\theta)\,, \tag{2}$$

with

$$\sigma_R^{(p\alpha)}(E_\alpha,\theta)=\sum_l \rho_l^{(3h)}(E_p-E_\alpha+Q_{g.s.})\sigma_{R,l}^{(BA)}(E_\alpha,\theta)\,, \tag{3a}$$

$$\sigma_R^{(p\alpha\alpha)}(E_\alpha,\theta)=\sum_{l_1l_2}\int \rho_{l_2}^{(ph)}(E'_\alpha-E_\alpha)\rho_{l_1}^{(3h)}(E_p-E'_\alpha+Q_{g.s.})\times\sigma_{R,l_2l_1}^{(BA)}(E_\alpha,E'_\alpha,\theta)dE'_\alpha\,, \tag{3b}$$

$$\sigma_R^{(pp\alpha)}(E_\alpha,\theta)=\sum_{l_1l_2}\int \rho_{l_2}^{(3h)}(E'_p-E_\alpha+Q_{g.s.})\rho_{l_1}^{(ph)}(E_p-E'_p)\times\sigma_{R,l_2l_1}^{(BA)}(E_\alpha,E'_p,\theta)dE'_p \tag{3c}$$

and similarly for $\sigma_L(E_\alpha,\theta)$.

In Eqs. (2) and (3), $(p\alpha)$, $(p\alpha\alpha)$, and $(pp\alpha)$, respectively, abbreviate (p,α), (p,α',α), and (p,p',α). In Eq. (3a), the $\sigma_{R,l}^{(BA)}(E_\alpha,\theta)$ is the right cross section obtained by performing the one-step first-order distorted wave Born approximation (DWBA) calculations, by assuming that the corresponding spectroscopic factor was unity. This is then multiplied by the spectroscopic density[2] $\rho_l^{(3h)}$ corresponding to the formation of the 3h states. The suffix l attached to both σ and ρ denotes the transferred orbital angular momentum. (Actually, it is an abbreviation for the pair of l and j, where $j=l\pm\frac{1}{2}$ is the total spin that is transferred.) Finally, $Q_{g.s.}$ is the Q value corresponding to the ground-state transition, and thus the argument $(E_p-E_\alpha+Q_{g.s.})$ of ρ is the excitation energy E_x of the residual nucleus. By summing over l the product $\rho_l\sigma_l$, we finally obtain $\sigma_R^{(p\alpha)}(E_\alpha,\theta)$. This is what is meant by (3a).

In (3b), $\sigma_{R,l_2l_1}^{(BA)}(E_\alpha,E'_\alpha,\theta)$ is the second order DWBA cross section. The first (p,α) step produces an α particle with an energy E'_α, and the second inelastic step reduces E'_α to E_α. The angular momenta transferred in these two steps are denoted, respectively, by l_1 and l_2. The fac-

tor $\rho_{l_1}^{(3h)}$ thus appears in (3b), just as $\rho_l^{(3h)}$ did in (3a). The spectroscopic density corresponding to the second step, creating a ph pair, is denoted by $\rho^{(ph)}$. Its argument $E'_\alpha - E_\alpha$ clearly describes the amount of additional excitation of the residual nucleus. The product $\rho_{l_2}^{(ph)}\rho_{l_1}^{(3h)}\sigma_{l_2 l_1}^{(BA)}$ is then integrated over E'_α from E_α to $E_p + Q_{g.s.}$, and summed over l_1 and l_2. This is what is meant by Eq. (3b). [To be more precise, the second order DWBA cross sections depend not only on l_1 and l_2, but also on $\vec{l} = \vec{l}_1 + \vec{l}_2$. We actually calculate the l-dependent cross sections first and sum them over l, obtaining $\sigma_{l_2 l_1}^{(BA)}$. We are able to carry out this summation, before the operations described by (3b) are carried out, because there is no other l-dependent factor in (3b).] What is meant by (3c) is understood in a similar way.

In carrying out the DWBA calculations, we used the (energy dependent) optical model parameters of Menet *et al.*[6] and of Sheperd *et al.*,[7] respectively, for the proton and the α channels. The calculations were performed, for simplicity in manipulating the spectroscopic densities, for the ^{90}Zr(p,α), rather than the ^{93}Nb(p,α) reaction. The ground state Q value for the ^{90}Zr(p,α) reaction is $Q_{g.s} = 6$ MeV.

As is well known, the DWBA cross sections vary smoothly with the energies. Thus, for the one-step processes, we first calculated the (p,α) cross sections for three choices of E_α: $E_\alpha = 71$, 53, and 35 MeV, i.e., for $Q = (E_\alpha - E_p) = 6$, -12, and -30 MeV. [In the following we shall refer to this triad of the Q values as (Q_1, Q_2, Q_3) or collectively as $\{Q\}$.] The cross sections for other E_α were then obtained by a logarithmic interpolation. For the two-step processes, accurate DWBA calculations were first performed for six pairs of Q values. The choices made were such that $(E'_\alpha, E_\alpha) = (71,71)$, $(71,53)$, $(71,35)$, $(53,53)$, $(53,35)$, and $(35,35)$ MeV for the (p,α',α) processes, and $(E'_p, E_\alpha) = (65,71)$, $(65,53)$, $(65,35)$, $(47,53)$, $(47,35)$, and $(29,35)$ MeV for the (p,p',α) processes. [Note that in either case we have $(E'_\alpha - E_p) = \{Q\}$ or $(E_\alpha - E'_p) = \{Q\}$.] The cross sections for other pairs of (E'_α, E_α) or of (E'_p, E_α) were obtained by using a two-dimensional logarithmic interpolation.

For the inelastic processes, either of protons or of α's, the first derivative of the optical potential was used as the form factor. As for the spectroscopic densities $\rho_l^{(ph)}(E_x)$, we used those of Ref. 8 rather than of Ref. 1. The former, containing the effect of the ground-state correlation, i.e., the collectivity effect, have larger magnitudes than do the latter, particularly for lower E_x.

In general, the form factor for the pickup of a cluster is given by a rather complicated sum over the various contributing partial form factors with different node numbers n and orbital angular momentum $\bar{l}$. In order to keep the problem numerically manageable we have chosen to take instead a set of representative form factors. They are independent of the transferred angular momentum but carry a Q-value dependence. Also, as will be discussed later, we had to take a different set of form factors for (p,α) and (p,α',α) and for (p,p',α). For (p,α) and (p,α',α) and $Q = Q_1$, Q_2, and Q_3 we used form factors with $(n,\bar{l}) = \{(n,\bar{l})\}_1 = (2,6)$, $(1,4)$, and $(0,4)$, respectively, while for (p,p',α) the corresponding set is $\{(n,\bar{l})\}_2 = (4.2)$, $(2,2)$, and $(1,2)$. (The values of $\bar{l}$ should not be confused with l_1 or l_2, the actual transferred angular momentum which ranges between 0 and 8 for all Q values.) Note that the above $(n,\bar{l})$ sets have the total (oscillator) quantum numbers $N = 2n + \bar{l} = 10$, 6, and 4. They are the representative values for the sum of quantum numbers of the three nucleons to be picked up for each choice of Q. The triton c.m. wave functions are calculated as bound in a Woods-Saxon potential, with the binding energy corresponding to the particular choice of Q. We used the same spectroscopic densities $\rho_l^{(3h)}(E_x)$ as in Ref. 2.

The results obtained in this way are compared with experiment in Fig. 1. The agreement with the experimental spectra [Fig. 1(a)] is very satisfactory, being similar to what it was in Ref. 2. (The theoretical cross sections given there were

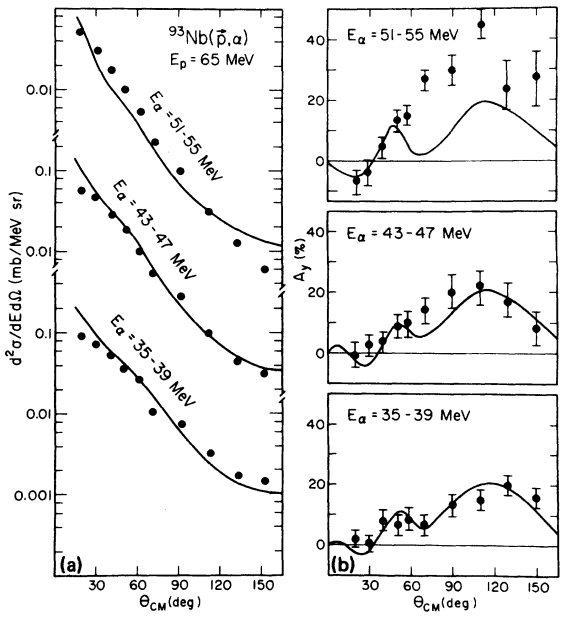

FIG. 1. Comparison of the present results, shown by solid lines, with data of Ref. 4. The left half (a) is for the cross sections, while the right half (b) is for analyzing powers.

of course obtained as $[\sigma_L(E_\alpha, \theta)+\sigma_R(E_\alpha, \theta)]/2$.) The agreement achieved here includes that of the absolute magnitude, in that the theoretical cross sections were obtained by using the N_0 factor (of the zero-range DWBA theory) equal to 350 MeV/$fm^{3/2}$ which is close to 500 MeV/$fm^{3/2}$ normally accepted for (p, α) calculations, and that the inelastic scattering was treated in exactly the same way as it was in Ref. 8.

The theoretical A_y [Fig. 1(b)] fits data both in magnitudes and angular distributions, particularly for the two lower E_α bins. At the highest E_α bin, however, the theory underpredicts experiment by a factor of about 2, for $\theta \gtrsim 60°$. A possible way to remove this difficulty may be to lift the degeneracy, which we have assumed for the two states with $j = l \pm \frac{1}{2}$ for a given l. As is well known,[9] the A_y's belonging to these two states all but cancel with each other.

The A_y's in all the energy bins are characterized by a large bump in the $\theta = 70°$–$160°$ region. Our calculations show that this bump is mainly due to the (p, p', α) process. The (p, p', α) process dominates the cross section and, as it is shown in Fig. 2 for the $E_\alpha = 43$–47 MeV bin, also the A_y's, particularly at large scattering angles.

We remarked above a different choice of the $(n, \bar{l})$ sets for (p, α) and (p, α', α) and (p, p', α) processes. We did this because it was found that the bump in A_y at large angles all but disappeared when a single $(n, \bar{l})$ set, either 1 or 2, was used throughout. We found, however, that only the pickup steps in which large angular momenta are transferred are responsible for this erratic behavior. Thus, it is possible to reproduce (approximately) the results of Fig. 1, even when, e.g., the set 1 is used throughout, if the set 2 is retained only for the $l_2 = 6 \sim 8$ transitions in the (p, p', α) process. Note that the form factors with the $(n, \bar{l})$ set 2 have longer tails than do those with the set 1. Since in the (p, p', α) process the pickup takes place from a highly excited target, the use of form factors with longer tails there may be not unreasonable.

In Refs. 1 and 2, we discussed our choice of simple shell-model configurations as (final) target eigenstates and the neglect of the interference between transitions to these states. Although we believe that the statistical arguments given there justify this approach, one may, of course, question the validity of using the statistical arguments to its extreme.

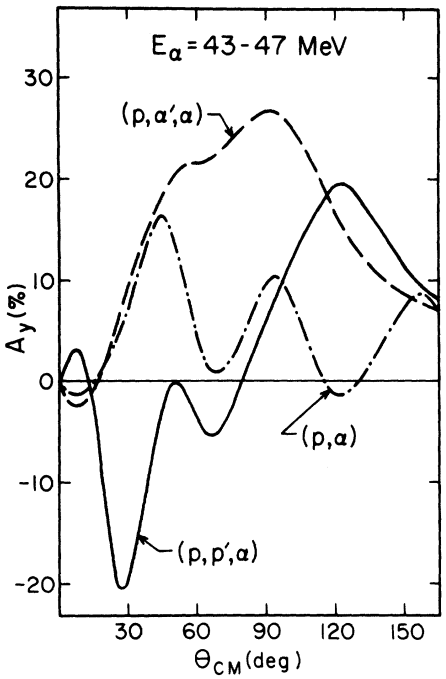

FIG. 2. The A_y's obtained when the three types of processes are considered separately.

There thus remains large room for further investigations. It is nevertheless gratifying to see, as shown above, that even with a rather simple type of calculation the data, including those of A_y, were explained rather well.

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