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STUDY OF THE TWO-STEP PROCESSES IN THE (*d*, *p*) REACTION ON RARE-EARTH NUCLEI

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The two-step model of the (*d*, *p*) reaction in rare-earth nuclei is investigated. The inclusion of nonelastic scattering in the entrance and exit channels improves the agreement between the calculated values and experimental data, but the discrepancies in the absolute strengths remain.

The single-step distorted-wave Born approximation (DWBA) is the method currently used for describing the stripping reaction. Such reactions have been studied in many regions of the periodic table, and valuable information on nuclear structure has been obtained. In the DWBA analysis the transition is assumed to proceed directly from the entrance to the exit channel without any excitation of the internal variables of the target and residual nuclei. However, in nuclei with low-lying collective states, such as in the region of deformed nuclei, a two-step process *via* excited states can give an important contribution to the direct reaction amplitude.

This problem has been investigated by several authors [2], [3], [4]. In one-particle transfer reactions, when strong coupling is important, it is possible to approximate the effects of coupling for the allowed transitions, while retaining the usual DWBA form [1].

In the case of deformed nuclei, when only the quadrupole deformation is taken into account, the only difference is the change from potential radii R_0 to $R_0\,(1+K_{Lj\Omega}\beta_2)$, where β_2 is the deformation parameter and

$$K_{lj\Omega} = \sqrt{2}\, C^{-1}_{lj\Omega} \sum_{l'j'} C_{l'j'\Omega}[5(2j'+1)/4\pi(2j+1)]^{\frac{1}{2}} \times$$

$$\times \langle 2j'0\Omega|j\Omega\rangle \langle 2j'0-\tfrac{1}{2}|j-\tfrac{1}{2}\rangle \tag{1}$$

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The C_{lj} coefficients are related to the Nilsson $a_{l\Lambda}$ coefficients by the relation:

$$C_{lj}(\Omega) = \sum_{\Lambda} \langle l\Lambda\tfrac{1}{2}\Sigma | j\Omega \rangle a_{l\Lambda}. \qquad (2)$$

In our previous paper [5] the modified DWBA method was applied to the (d, t) reactions on rare-earth deformed nuclei. It is interesting to check the above mentioned model for the (d, p) reactions for the same states as those in the (d, t) reaction.

The two reactions (d, t) and (d, p) are one-neutron transfer reactions described quite well by the stripping theory of Satchler [6] with the nuclear wave functions of Nilsson [7] and the intrinsic particle cross-sections given by the usual distorted-wave Born approximation (DWBA). However, for some transitions observed in the (d, t) and (d, p) reactions on rare-earth nuclei a discrepancy is observed between the calculated and measured angular distributions [8], [9].

In our previous paper [5] the agreement between calculated and experimental data was improved by the inclusion of the nonelastic scattering effect into the triton angular distributions for the (d, t) reactions.

The angular distributions for the (d, p) reactions can be described as follows [6]:

$$\frac{d\sigma^{(+)}}{d\Omega} = 2N^{(+)} C_{lj}^2 \sigma_l^{(+)}(\theta) U_\nu^2. \qquad (3)$$

As is seen, the coupling phenomena (like the Coriolis coupling or $\Delta N = 2$) have been neglected. $N^{(+)}$ is a normalization constant which is equal to 1.5 for a (d, p) reaction if the Hulthén wave function is used for the deuteron. $\sigma_l^{(+)}(\theta)$ is the cross-section which can be calculated by means of the DWBA. U_ν^2 is the probability that the state ν into which the neutron is stripped is empty.

In our calculations of the cross-sections we used a modified GAP-2 code [10][1] without the spin-orbit term. The coefficients C_{lj} for the appropriate Nilsson states were taken from the table given by Chi [11]. The deuteron and proton optical parameters used are listed in Table I. The parameters are those which are widely used for the stripping analysis in the rare-earth mass region [12].

TABLE I

Optical-model parameters for deuterons and protons

	V (MeV)	W (MeV)	r_0 (fm)	a (fm)	r_0' (fm)	a' (fm)
Deuterons	104	17	1.15	0.81	1.34	0.68
Protons	54	17	1.25	0.65	1.25	0.47

To test the model proposed by Kunz *et al.* [1] we select the 1/2 1/2⁻[521], 3/2 3/2⁻[521] and 7/2 3/2⁻[521] states which were also analysed for the (d, t) reaction in our previous

[1] Modified by E. Wesołowski.

paper [5]. The calculated values of K and ΔR_0 are listed in Table II. The absolute values of the cross-sections for the (d, p) reaction which populate the 1/2 1/2⁻[521], 3/2 3/2⁻[521] and 7/2 3/2⁻[521] states were obtained from formula (3). To compare the results given by the model proposed by Kunz *et al.* [1] with those found from ordinary DWBA calculations, the absolute values of the cross-sections were reduced to the same value of $Q = 3$ MeV. The U_v^2 parameters were the same as those used by Kanestrøm and Tjøm in the DWBA calculation for the (d, p) and (d, t) reactions [13], [14].

TABLE II

The $K_{lj\Omega}$ coefficients for the investigated states

Nilsson assignment	$K_{lj\Omega}$	β_2	ΔR_0
1/2 1/2 — [521]	0.40	0.3	0.12
3/2 3/2 — [521]	0.44	0.3	0.13
7/2 3/2 — [521]	0.08	0.3	0.02

When applying the model proposed by Kunz *et al.* [1] all effects, except nonelastic scattering, which give a deviation from the one step direct reaction populating pure rotational states, must be excluded. The Coriolis coupling is the most important effect which disturbe the pure rotational structure of the investigated states. The influence of the Coriolis coupling on the (d, p) and (d, t) cross-sections has been studied in Refs [13], [14] for several nuclei in the mass region of 153–171. In the present paper we assume that the states for which the cross-sections calculated with and without inclusion of Coriolis coupling are nearly the same can be treated as being free of Coriolis coupling. In Table III we compare the theoretical, theoretical mixed, theoretical modified and experimental values of the (d, p) reaction cross-sections for the appropriate states. The theoretical values were found using

TABLE III

Comparison of the experimental and theoretical cross-sections in the investigated nuclei

State	Isotope	Energy (keV)	(d, p), 90° (μb/sr) $Q = 3$ MeV			
			exp.	theory	mix[a]	mod.
1/2 1/2 — [521]	^{155}Sm	821	253	270	253[a]	170
	^{167}Er	208	217	215	217	145
	^{171}Yb	0	103	98	99	63
3/2 3/2 — [521]	^{155}Sm	0	103	108	—	54
	^{167}Er	750	41	9	2	7
7/2 3/2 — [521]	^{155}Sm	125	208	252	—	219
	^{167}Er	894	90	18	5	17

[a] Refs [13], [14].

formula (3). The theoretical mixed cross-sections were calculated in paper [13] by means of the formula

$$\frac{d\sigma}{d\Omega} = 2N^{(+)}[\sum_i C^i_{lj} a_i U_i (\sigma^i_l(\theta))^{\frac{1}{2}}]^2 \tag{4}$$

where the summation over i is performed over bands which are coupled. The a_i are the mixing amplitudes due to Coriolis coupling. The angular functions $\sigma^i_l(\theta)$ are obtained from the DWBA calculations using the deuteron and proton optical model parameters

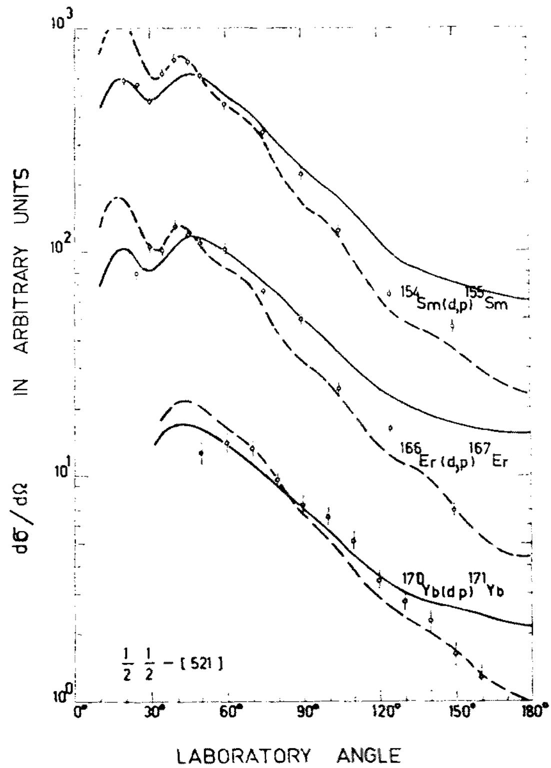

Fig. 1. Angular distributions for proton groups with $l = 1$ (Nilsson state 1/2 1/2 — [521]). The solid line shows the result of a DWBA calculation. The dashed line shows the modified DWBA calculation (E_d = 12.1 MeV)

shown in Table I. The theoretical modified cross-sections were calculated from formula (3) with the optical model parameters modified to provide for nonelastic scattering in exit and entrance channels.

The corresponding modified DWBA calculations of the angular distributions are presented in Figs 1–3. The agreement with the experimental results seems to be better (except 3/2 3/2–[521] for the ^{166}Er (d, p) ^{167}Er reaction) for the modified DWBA calculation (dashed lines) than for the normal DWBA calculations (solid lines).

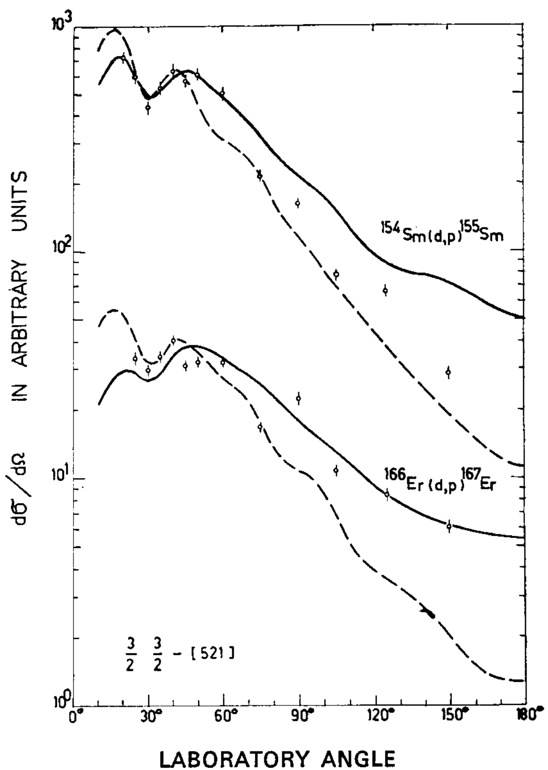

Fig. 2

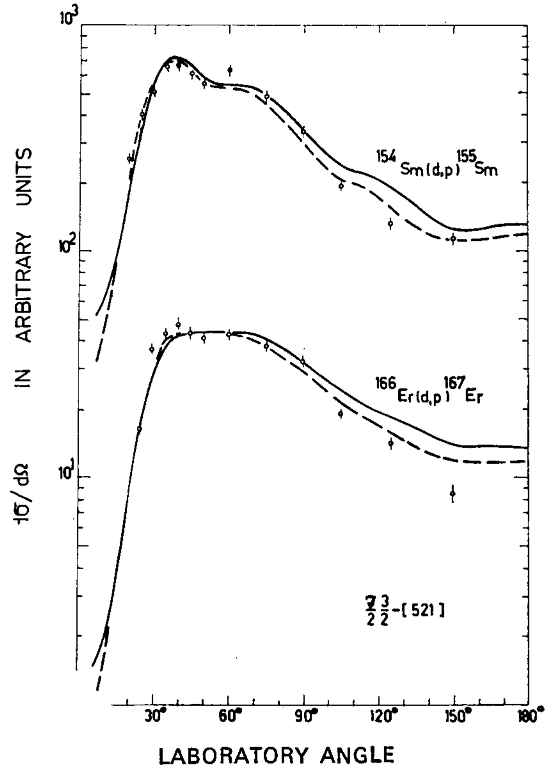

Fig. 3

Fig. 2. Angular distributions for proton groups with $l = 1$ (Nilsson state 3/2 3/2 — [521]). The solid line shows the results of a DWBA calculation. The dashed line shows the modified DWBA calculation ($E_d = 12.1$ MeV)

Fig. 3. Angular distribution for proton groups with $l = 3$ (Nilsson state 7/2 7/2 — [521]). The solid line shows the result of a DWBA calculation. The dashed line shows the modified DWBA calculation ($E_d = 12.1$ MeV)

As can be seen from Table III, the 1/2 1/2–[521] states in ^{167}Er and ^{171}Yb are almost free from Coriolis coupling. The same can be said about the ^{155}Sm nucleus, but only by comparison with the same state in ^{153}Sm [14]. The modified absolute values of the cross-section obtained for 90° are too small. This means that the Kunz model gives too large values of nonelastic cross-sections for d and p on the considered isotopes. The same holds for the states 3/2 3/2–[521] in ^{155}Sm and ^{167}Er nuclei if the influence of the Coriolis coupling can be neglected.

For the 7/2 3/2–[521] states in ^{155}Sm and ^{167}Er the modified DWBA calculations give better agreement with experimental data, but oving to strong Coriolis mixing this agreement is rather incidental.

To conclude we can say that as far as angular distributions are concerned the inclusion of nonelastic scatering improves the agreement between the calculated values and experimental data, but the discrepancies in the absolute strenghs remain.

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