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The multi-step nucleon transfer process is connected with preliminary and posterior excitations of the low-lying collective states in the entrance and exit channels. In some details multi-step effects have been investigated in deuteron stripping reactions in the case of deformed nuclei only (see e.g. refs. [1-3]). They were shown to play an important role and often can be of the same order as the direct one-step transitions going without any intermediate excitations. Note, that in this case it was natural to use an appropriate method of the strongly coupled channel consideration.

In the case of spherical nuclei such a consideration has not been yet done,with the exception of only two attempts of indirect transfer calculations which were performes in refs.[4,5] and based on a specific "core-excitation stripping model".In this paper we treat another more general method,the so-called generalized distorted wave Born approximation(GDWBA)which was confirmed very well beforehand by the calculations of the multi-step stripping reactions on deformed nuclei.To this end we use the result of the previous work[6] where in the framework of the mentioned above GDWBA method with the corresponding generalized distorted waves calculated under a suggestion of the so-called double adiabatic perturbation theory an expression for the multi-step cross section has been obtained. The main advantage of using this perturbation approach is the possibility of giving the multistep cross section in a very simple and handy form, so all the calculations may be carried out with the help of the standard everywhere known DWBA-method (see e.g. ref. [7]). This perturbation approach seems to be a good one because of an experimental fact of smallness of inelastic transition probabilities of phonon states in spherical nuclei, comparing to those of rotational states in deformed nuclei. Thus, the corresponding multi-step transfer amplitudes, which are proportional to these probabilities, should also be in the same relations. Therefore one may hope that the corresponding multi-step stripping calculations on spherical nuclei can be done successfully with the help of the perturbation treatment. Naturally, in practice all the cases need control: does really this approach hold.

We limit ourselves to the consideration of only two-step stripping reactions $A(dp)B$ on even nuclei, when intermediate transitions via the one-phonon states only are taken into account. In this case the corresponding formulae take the following obvious form [6]:

$$\frac{d\sigma}{d\Omega}(\theta) = \frac{2J_B+1}{2J_A+1} \sum_{Lm} \Big/ c \sum_{\ell} \hat{B}_{\ell}^{L} \beta_{\ell}^{Lm}(\theta) \Big/^2 , \qquad (1)$$

where c is the usual numerical constant, and

$$\beta^{Lm} = D_0 \sum_{\ell_p \ell_d} (-1)^{\ell_p} \frac{\hat{\ell}_p \hat{\ell}_d^2}{4\pi \hat{L}^2} (\ell_p \ell_d m0 / Lm)(\ell_p \ell_d 00 / L0) Y^*_{\ell_p m}(\hat{k}) \int r^2 dr\, \phi_{\ell_p} R_{\ell} \phi_{\ell_d} \qquad (2)$$

is the modified (when $L \neq \ell$) one-step stripping amplitude, which can be easily calculated by the ordinary DWBA-method. In the case when the transferred momentum L coincides with a captured neutron orbital momentum ℓ the $\beta_{\ell}^{\ell m}$ amplitude is exactly the same as that of the DWBA-code. A spectroscopic part of the cross section is included in a weight-step factor:

$$\hat{B}_{\ell}^{L} = \sum_{aIj} \gamma_{Ij\ell}^{aB} (-1)^{I+j-J_B} \hat{j}\hat{\ell}(\ell 100/L0) W(jJ_B \ell L; Is_n) \hat{A}_I(aA), \qquad (3)$$

where

$$\gamma_{Ij\ell}^{aB} = \sum_{\nu M} (IjM\nu / J_B M_B) < J_B M_B B / a^+_{j\ell\nu a} / IMa > \qquad (4)$$

are the generalized spectroscopic amplitudes, which denote the quasiparticle ($I=0$), quasiparticle + phonon ($I=$ 2,3) and other higher components in the whole odd nucleus wave function $|J_B M_B B>$. Here the $|IMa>$ is a wave function of the initial even nucleus in the ground ($I=0$), or excited states ($I \neq 0$). It is obvious that the quasiparticle component $\gamma^{AB}_{0J_BL}$ determines the usual stectroscopic factor $S_L = /\gamma_L/^2$. Then, the operator

$$\hat{A}_l = \delta_{l0}\,\delta_{\alpha A} + a_l\left(R_p \frac{\partial}{\partial R_p} + R_d \frac{\partial}{\partial R_d}\right) \tag{5}$$

adjusts a contribution of each step into the stripping amplitude. The coefficient a_l is just proportional to a reduced matrix element of the phonon states excitation

$$a_l = \frac{\hat{l}\sqrt{4\pi}}{3A\ R_d^l} < l\ \|\hat{\mathfrak{M}}_l\|\ 0 > , \tag{6}$$

where

$$\hat{\mathfrak{M}} = \sum_{i=1}^{A} r_i^l\ Y_{lM}(\hat{r}_i) \tag{7}$$

is a mass transition l -multipolarity operator. In principle, the magnitude of a_l can be extracted independently from the corresponding experimental inelastic cross sections. Also, it can be calculated in the framework of an appropriate nuclear model or expressed through an electric transition probability by means of introducing a dimesionless effective charge e_{ef} and an effective nucleon mass q_{ef} parameters $(q_{ef}/e_{ef} \sim A/Z)$:

$$a_l = \left(\frac{q_{ef}}{e_{ef}}\right)\frac{1}{e}\ \frac{\hat{l}\sqrt{4\pi}}{3A\ R_d^l}\ B^{1/2}_{l\to 0}(El) \ . \tag{8}$$

Note, that the well known perturbation result of ref. /2/ for the two-step cross section of deformed nuclei follows from our equations, putting instead of $B(El)$ the classical rotational model formula, so that a_l becomes equal to $\beta/\sqrt{4\pi}$, where β is the static deformation parameter.

With the help of the above given expressions numerical applications were carried out for the stripping reaction $^{52}Cr(dp)\ ^{53}Cr$ leading to the following states $3/2^-$(g.s.), $1/2^-$(0.567MeV), $5/2^-$(1.01MeV), $3/2^-$(2.32 MeV). The main purpose of this investigation was to find out typical features of two-step corrections to one-step transitions on these states. Calculations were based on the ordinary DWBA code [7] which was modified slightly due to the necessity of taking into account the small change ($L \neq \ell$) in the amplitude (2). The mixture coefficients γ were taken as given by the core-excitation model in ref. [8] (see Table). A set of optical parameters is the same as in ref. [9]. The coefficient a_2 was chosen equal to 0.031, corresponding to a known experimental $B(E2)$ probability.

Now consider the obtained results.

1. First of all, one can see from Table that the contributions of two-step effects are rather small and amount approximately to 1-3% of the one-step cross section. Thus, this result confirms the previous qualitative estimates [6] and also quantitative calculations in the framework of the "core-excitation stripping model" [5].

2. On the other hand, one can see the fast increasing of the relative two-step effect contributions (about two orders) with an increasing of the nuclear state excitation energy (from g.s. $(3/2^-)_1$ to 2.32 MeV $(3/2^-)_2$). The reason of that is a more complicated structure of high-lying nuclear states and, in particular, a more important role of the higher nuclear component admixtures.

3. However, we can conclude that the smallness of two-step effects in an absolute value makes oneself sure that they really may be treated in the framework of perturbation approach. The other point is that in practice the presented formalism is rather convenient since it uses the ordinary DWBA code only.

4. Figure 1 is a typical picture which demonstrates an influence of two-step effects on an angular distribution in a (dp) stripping reaction. On the right side of Fig. 1 the pure effect of the square two-step amplitude only is shown. As is easily seen a two-step contribution is peaked at the angles near the principal maximum of a one-step differential cross section and results in a more smooth summarized curve.

5. Figure 2 shows the magnitude of two-step effects at a twice increased deuteron energy equal to $E_d = 20$ MeV. We see that now the two-step contribution is about 10% of the one-step cross section, i.e. 10 times larger than at $E_d = 10$ MeV. Of course, this fact is due to an increasing role of virtual one-phonon state excitations.

6. Then, Fig. 3 gives a comparison between an "exact $(L \neq \ell)$" and an "approximate $(L = \ell)$" way of computing the two-step amplitude (2). The aim of this comparison is to investigate whether we can always use the ordinary DWBA code which calculates the only β_ℓ^m amplitude $(\ell = L)$ and not use its modification for the general case $(\ell \neq L)$, which needs more computing time. We see that the way of putting

$L - \ell$ in eq. (2) in all the cases results in about a 20% change in two-step contributions. Therefore one can conclude that for the purpose of the qualitative estimation it is possible really to calculate two-step stripping without increasing the computational difficulties. In this case the only necessity is to found out the derivatives of the standard amplitudes β_ℓ^{m} by means of calculating them practically only at five points of R_p and R_d with a shift from one another by about 0.2 fermi. The parameters R_p and R_d are those of optical potentials in entrance and exit channels.

7. Finally we note that here we have analyzed the two-step effects in allowed, generally strong transfer transitions only. They occur with large probabilities which is due to comparatively large magnitudes of quasiparticle components in the odd nucleus wave functions. However it is obvious that the two-step effects must play a decisive role in the case of forbidden, generally one-two order weeker, transitions. These latter are observed experimentally rather often but remain without any identification. An analysis of them in the framework of a multi-step stripping mechanism is of great theoretical interest because of the possibility of determining the nature of higher components in the nuclear wave functions.

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Table

The expansion core-excitation γ -coefficients/8/ of the odd nucleus ^{53}Cr wave function and the relative contributions of two-step effects in the stripping reaction $^{52}Cr(dp)\,^{53}Cr$ at $E_d = 10$ MeV

$J_B L$ (E MeV)	$\gamma_{0 J_B L} = \sqrt{S_L}$	$\gamma_{2 j \ell}$			$max \left\| \frac{d\sigma - d\sigma_{one-step}}{d\sigma} \right\| \%$
	$j = J_B$ $\ell = L$	$j = 1/2$ $\ell = 1$	$j = 3/2$ $\ell = 1$	$j = 5/2$ $\ell = 3$	
$3/2^-$ 1 (g.s)	0.832	-	-0.444	-0.077	0.02
$1/2^-$ 1 (0.576)	0.447	-	0.834	-0.212	1.15 (11.2)x/
$5/2^-$ 3 (1.01)	0.185	-0.381	0.433	-0.13	2.8
$3/2^-$ 1 (2.32)	0.507	-0.151	0.799	-0.068	1.31

x/The two-step contribution at $E_d = 20$ MeV.

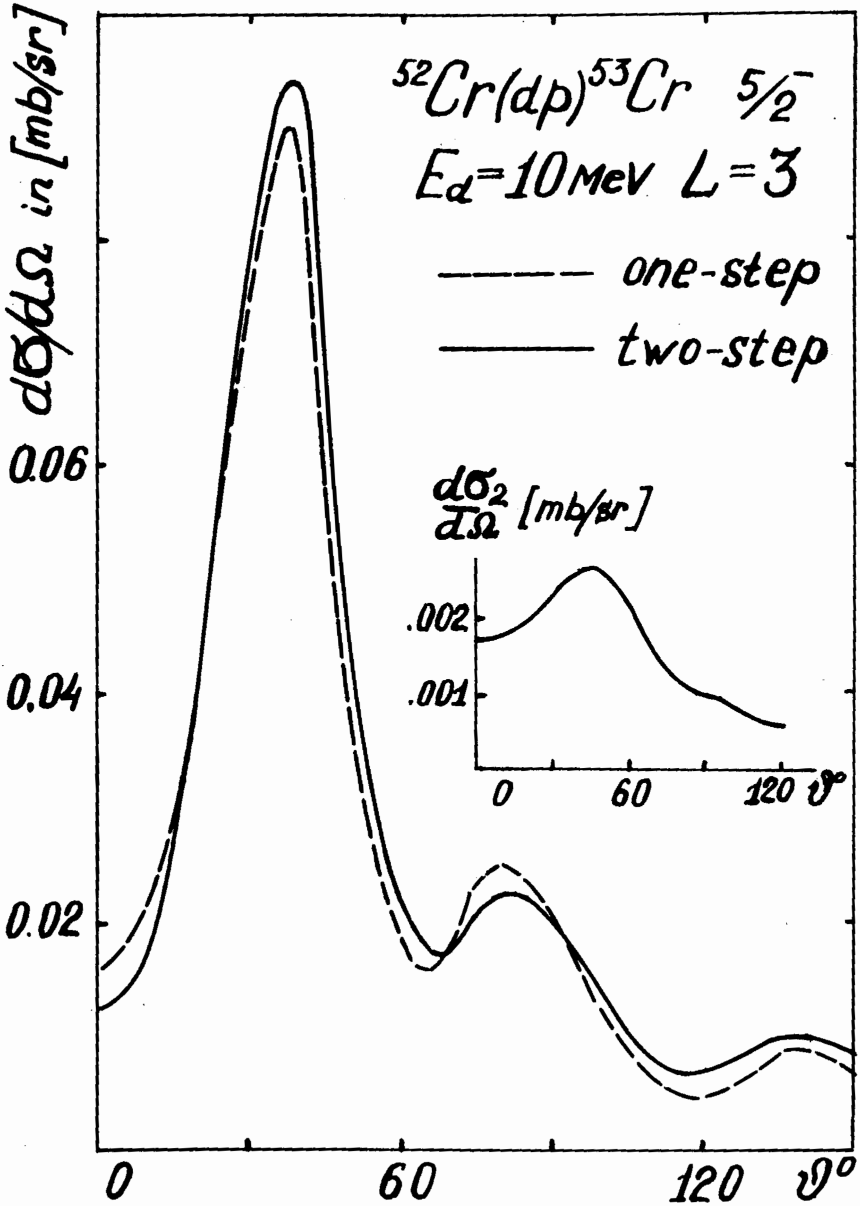

Fig. 1. Differential cross sections of the one- and two-step transferring in (dp) stripping at E_d = 10 MeV. On the right the pure two-step cross section is shown, when the one-step amplitude is taken to equal zero.

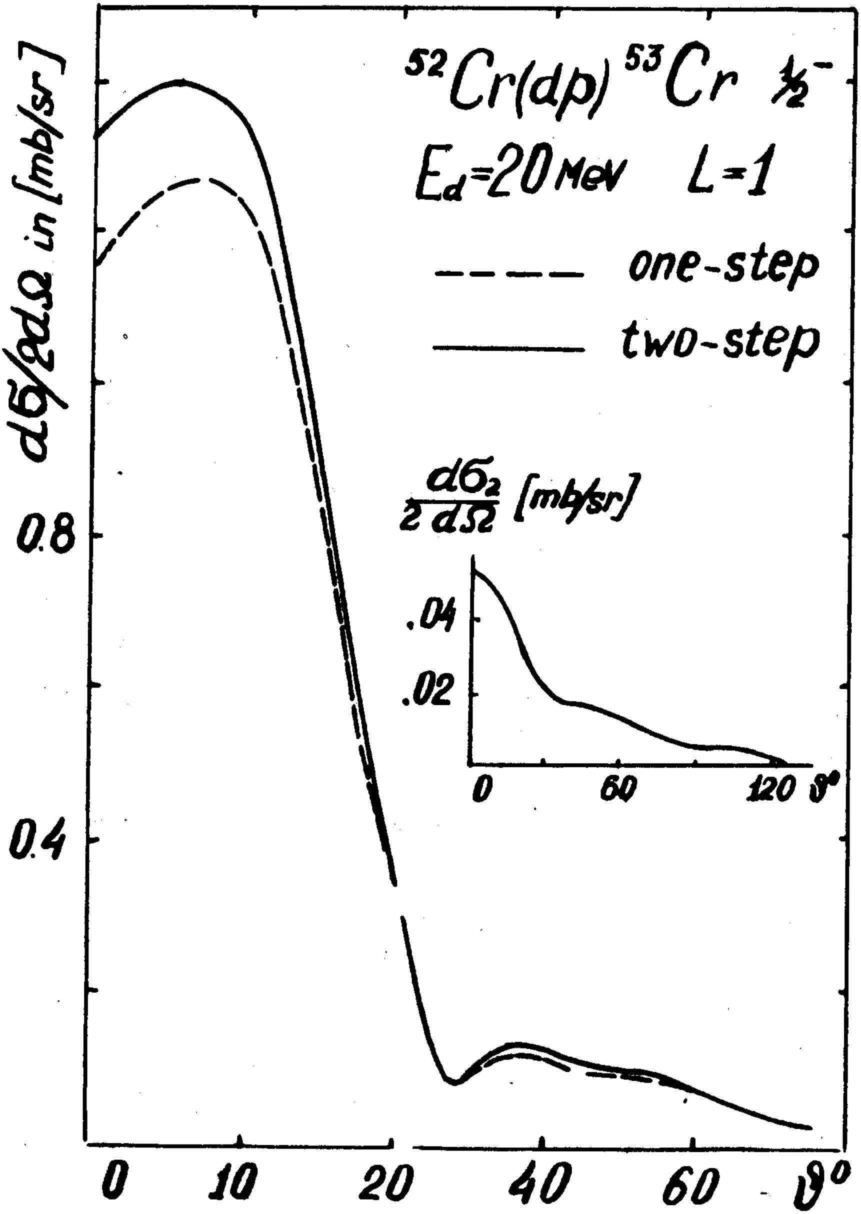

Fig. 2. Differential cross section (devided by 2) of the one- and two-step nucleon transferring at E_d = 20 MeV. On the right is the pure two-step effect.

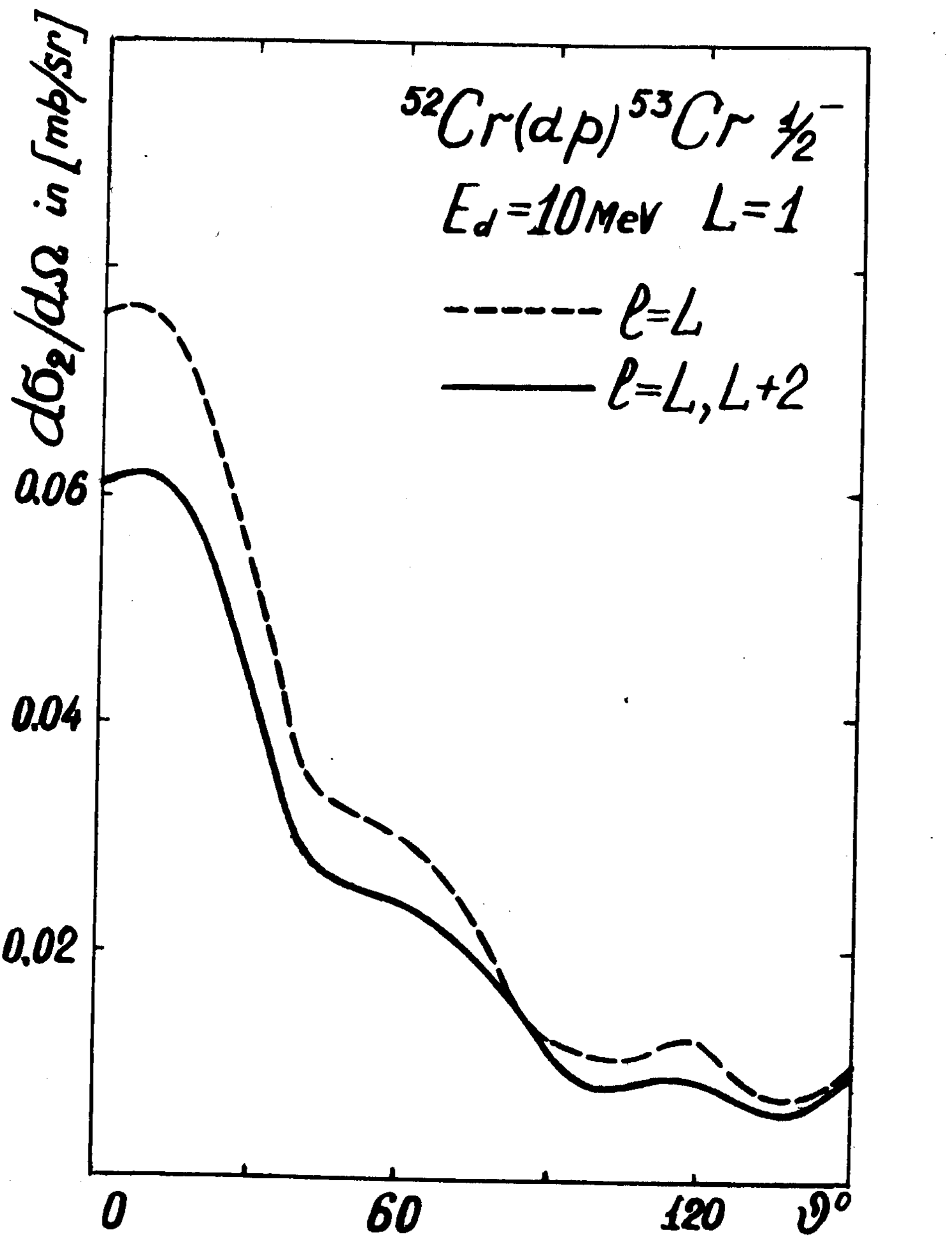

Fig. 3. A comparison of the two-step effects, calculated by means of an "exact" (all ℓ) and an "approximate" ($\ell = L$) methods (see the text).