Acta Universitatis Carolinae. Mathematica et Physica

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Acta Universitatis Carolinae. Mathematica et Physica, Vol. 17 (1976), No. 1, 55--64

Persistent URL: http://dml.cz/dmlcz/142379

1976 ACTA UNIVERSITATIS CAROLINAE – MATHEMATICA ET PHYSICA VOL. 17, NO. 1, Pag. 55–64

The Deuteron and Triton Optical Potentials for the ^{162}Dy(d, p) and ^{162}Dy(d, t) Reactions at $E_d = 12.1$ MeV

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Received 27 November 1974

The optical potentials of deuterons and tritons, used in the DWBA analysis of the (d, p) and (d, t) reactions on the ^{152}Dy nucleus at 12.1 MeV deuteron energy were examined. The parameters of the potentials were fitted to the experimental angural distribution of the 12 MeV deuterons elastically scattered by the ^{162}Dy as well as to the experimental angural distributions of protons and tritons emergent from the deuteron induced reactions. The discussion of different sets of parameters is presented.

В работе были исследованы оптические потенциалы дейтонов и тритонов, используемые в борновском приближении с искаженными волнами для анализа (d, p) и (d, t) реакций на ядре ^{162}Dy при энергии 12.1 мев. Параметры потенциалов подгоднялись как на экспериментальное угловое распределение дейтонов с энергией 12 мев, упруго рассеянных на ^{162}Dy, так и на экспериментальные угловые распределения протонов и тритонов, вылетающих из реакций, вызванных дейтонами. Различные наборы параметров овсуждаются с точки зрения согласия рассчитанных распределений с экспериментом.

V práci jsou studovány deuteronové a tritonové optické potenciály, používané v metodě Bornova přiblížení s porušenými vlnami při analýze reakcí (d, p) a (d, t), vyvolaných deuterony o energii $E_d = 12{,}1$ MeV na jádře ^{162}Dy. Parametry optických potenciálů byly fitovány jak na experimentální úhlové rozdělení deuteronů s energií 12 MeV, elasticky rozptýlených na jádře ^{162}Dy, tak i na úhlová rozdělení protonů a tritonů, vznikajících při reakcích s deuterony. Různé soubory parametrů jsou diskutovány z hlediska souhlasu vypočtených rozdělení s experimentem.

I. Introduction

In papers [1, 2, 3] the deuteron induced reactions on ^{162}Dy nucleus were studied using the Distorted Waves Born Approximation (DWBA) theory. In such an analysis good knowledge of the optical potentials for the input and output channels is necessary [4, 5]. Because the theoretically derived potentials (e.g. [6]) are rather approxi-

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mative and can hardly be used for the extraction of the spectroscopic informations from the direct stripping and pick-up nuclear reactions, the fitting of the optical potentials parameters to the experimental elastic scattering angular distributions is usually used (e.g. [7, 8]). Nevertheless, such a way is not fully consistent with the mechanism of the nuclear reactions because the elastic scattering is determined mainly by the asymptotical behaviour of the wave functions while the transitions in the nuclear reactions are strongly influenced by the detail form of the wave functions in the vicinity of the nucleus. Moreover, the fitting to the elastic scattering only can bring some ambiguity in determination of the optical potentials [8]. Therefore, a simultaneous study of the reaction angular distributions can be useful in finding more realistic optical potentials describing the elastic scattering as well as some other processes. This method was used in the present work and the deuteron and triton optical potentials, convenient for the ^{162}Dy(d, p) and ^{162}Dy(d, t) reactions at $E_d = 12.1$ MeV were found.

2. Theoretical considerations

The extraction of the optical potentials was based on the comparison of the experimental angular distribution with the theoretical predictions, calculated by the DWBA method for different transferred angular momenta, l. The optical potentials of the nucleus were used in the form

$$V(r) = -Uf(r) - iWg(r) + V_c(r) \tag{1}$$

$$f(r) = \frac{1}{1 + \exp\left(\frac{r - \varrho A^{1/3}}{\alpha}\right)} \tag{2}$$

$$g(r) = \frac{4 \exp\left(\frac{r - \varrho' A^{1/3}}{\alpha'}\right)}{\left[1 + \exp\left(\frac{r - \varrho' A^{1/3}}{\alpha'}\right)\right]^2} \tag{3}$$

Here, U is the real part of the central nuclear potential, W is the imaginary part, which was taken in the surface form and $V_c\,(r)$ is the Coulomb potential of the nucleus. The geometrical parameters ϱ, ϱ' and α, α' are the radius parameters and surface diffusenesses respectively. The spin-orbital part of the optical potential was not taken into account because, in the energy region studied, it influences the angular distributions very weakly [2, 8] and the polarisation effects were not measured.

The parameters of the deuteron and triton optical potentials were found by fitting the experimental angular distributions of elastically scattered deuterons as well as by fitting the experimental angular distributions of protons and tritons from the (d, p) and (d, t) reactions. The optimalization computer program OMAS [9], adapted for the GIER computer, was used for the elastic scattering analysis. It is based on the Oxford-Oak-Ridge optimalization method [10] and permits simultaneous search for as much as 13 parameters.

The reaction angular distributions were fitted by special computer program, written by one of the authors (P. H). It is based on the combination of the DWBA program [11] with the optimalization subroutine from OMAS and was adapted for the ODRA-1204 computer.

3. The result of analysis

In the DWBA analysis of the (d, p), (d, d') and (d, t) reactions the optical potentials for the protons, deuterons and tritons are necessary. The parameters, used for the analysis of the ^{162}Dy(d, p) and ^{162}Dy(d, t) reactions [2, 3] were found as a result of detailed analysis of proton and triton angular distributions for the known strongest transitions by the method, described in Part 2 of the present paper. Because the proton optical potential for the rare earth deformed nuclei was analysed rather carefully by Perey [7] and by Siemssen and Erskine [8], the proton parameters from reference [8] were used in the paper [2]. We found, in agreement with Siemssen

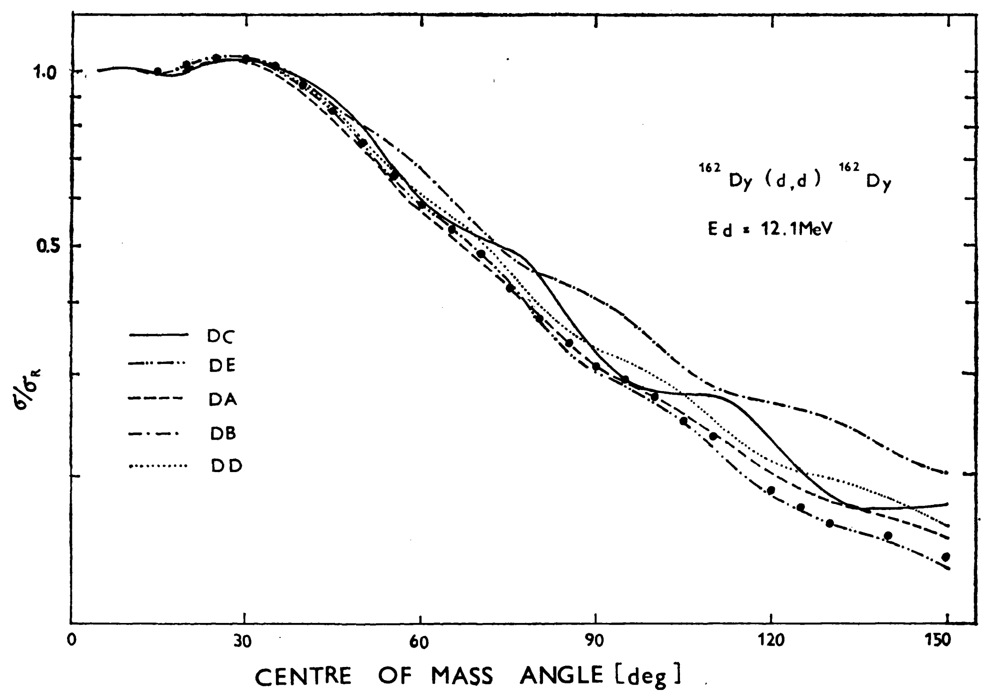

Fig. 1. Angular distribution of the elastic scattering of deuterons. The experimental data are taken from ref. [15], the optical potential parameters from [7, 8, 13, 14, 15] (see table 1.)

Table 1. The deuteron optical potentials

Potential	U[MeV]	W[MeV]	ϱ[fm]	ϱ'[fm]	α[fm]	α'[fm]	Source
DA	113.7	22.6	1.15	1.36	0.901	0.709	[8]
DA′	118.1	13.4	1.18	1.36	0.842	0.940	[12]
D 1	120.3	21.2	1.16	1.30	0.858	0.760	
DB	104.0	17.0	1.15	1.34	0.81	0.68	[13]
D 2	84.6	18.3	1.22	1.32	0.850	0.761	
DC	86.0	12.0	1.15	1.37	0.87	0.70	[14]
D 3	80.0	20.1	1.26	1.31	0.824	0.746	
DD	77.0	20.4	1.30	1.37	0.79	0.67	[7]
D 4	82.2	19.1	1.23	1.32	0.840	0.755	
DE	90.2	16.8	1.15	1.33	0.91	0.77	[15]

and Erskine, that the (d, p) angular distributions are rather weakly affected by the changes in the proton parameters [2]. Therefore no special search for these parameters was done.

3.1 THE DEUTERON OPTICAL POTENTIAL

The parameters of the deuteron optical potentials, analysed in the present work are collected in table 1. The potentials marked as *DA—DD* were used by other authors for (d, p) and (d, t) reactions on different rare earth deformed nuclei [7, 8, 12, 13, 14], while the set DE is that obtained as a 5-parameter fit by Christensen et al. from the deuteron elastic scattering angular distribution [15]. It is substantial that the potentials *DB*, *DC* and *DD* describe the deuteron elastic scattering rather badly, as is seen from Fig. 1.

We used the parameters *DA—DD* as the starting sets for the analysis of the experimental deuteron elastic scattering angular distribution, measured by Christensen et al. [15]. 25 values for the region of angles from 20° to 150° were used. By the optimalization procedure, described in part 2, all six parameters of the optical potential (U, W, ϱ, ϱ', α and α') were fitted simultaneously. As a result, the parameter sets *D*1—*D*4 were found[a]) all giving about the same results for the elastic scattering angular distribution ($\chi^2 \doteq 20$ for all sets). Therefore, it is impossible to find the deuteron optical potential on the basis of the elastic scattering angular distribution only.

In the next step, we used the DWBA method and the angular distributions of protons from the ^{162}Dy(d, p) ^{163}Dy reaction for the strong transitions to the well--known states were examined. The transitions to the 351 keV and 801 keV levels

[a]) The starting potentials *DA* and *DA′* bring the sets, differing less than by 1% in all six parameters and therefore only one set, marked as *D* 1, was used in the further analysis.

in ^{163}Dy nucleus were employed, being known to be rather pure $l = 1$ and $l = 3$ transitions respectively [2]. The comparison of the experimental angular distributions and distributions calculated with different potentials is shown in Fig. 2 (the curves for the potential $D\,4$ are not given because they are very

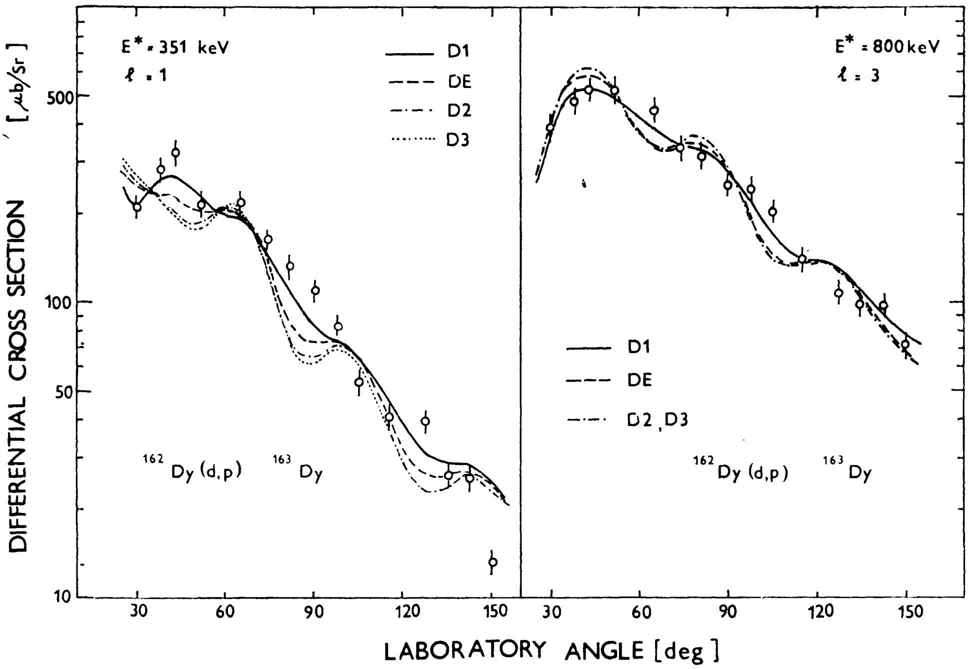

Fig. 2. Comparison of the experimental angular distributions of protons for the $l = 1$ and $l = 3$ transitions in the (d, p) reaction with the DWBA predictions. For the potential used see table 1

close to that for $D\,3$ parameters). It is seen that only the potential $D\,1$ fits the experimental results while the angular distributions calculated with the $D\,2$—$D\,4$ and DE potentials differ rather strongly from the experimental ones. Therefore we suggest the deuteron optical potential $D\,1$ as the most convenient for simultaneous description of elastic scattering as well as for the description of reactions, induced by the deuterons of ~12 MeV energy.

3.2 THE TRITON OPTICAL POTENTIAL

The determination of the triton optical potential is rather difficult. The theoretical expectations are very uncertain owing to the complex structure of triton. On the other hand, the elastic scattering of tritons by complex nuclei can be measured only on a few accelerators arranged for the triton beam (on the ground of the triton's radioactivity) and the available results are very scarce. In this case, some valuable information can be obtained from the study of the reactions, producing tritons as the outgoing particles. This hope is supported by the succesful use of the (*d*, *p*) reaction for the precissement of the deuteron optical potential.

In the present work the experimental angular distributions of tritons from the ^{162}Dy(*d*, *t*) ^{161}Dy reaction at 12.1 MeV energy of incident deuterons were used for

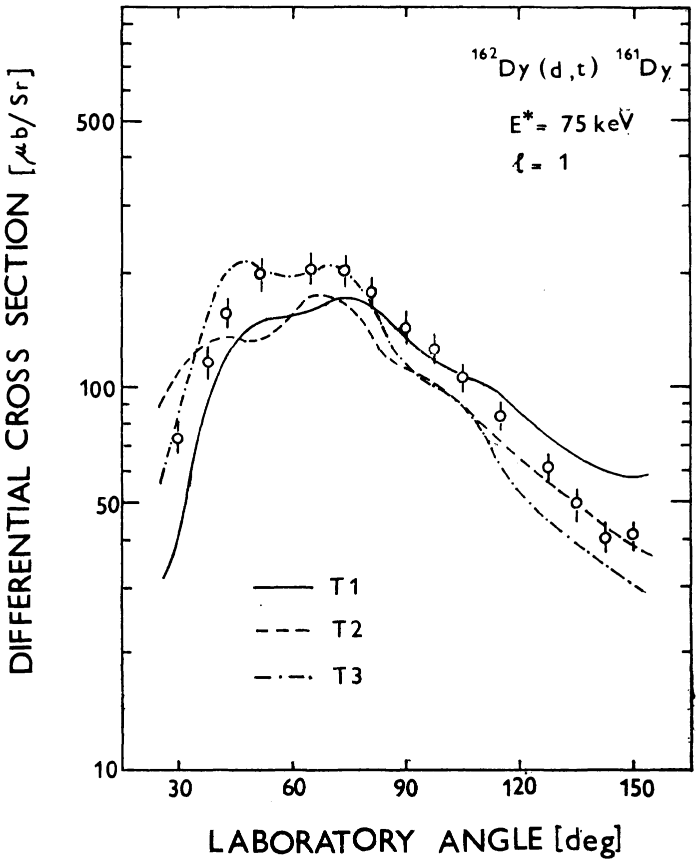

Fig. 3. Angular distributions of tritons from the (*d*, *t*) reaction for the $l = 1$ transition. The DWBA predictions were calculated with the potentials taken from ref. [16, 17, 18] (see table 2.)

extraction of the triton optical potential parameters. The analysis was made by the method, described in the last paragraph of Part 2 and the deuteron optical potential *D* 1 was used elsewhere. The absolute cross sections at 15 angles in the region from 30° to 150° were measured. The strong transitions to the well-known states in ^{161}Dy at 75 keV ($l = 1$) and 608 keV ($l = 0$ transition) [3] were used for the analysis. In the last analysis some other known strong transitions with different *l*-values, leading to the excited states in ^{161}Dy below 800 keV excitation energy were also

Table 2. The triton optical potentials

Potential	U[MeV]	W[MeV]	ϱ[fm]	ϱ'[fm]	α[fm]	α'[fm]	Source
T 1	154.0	12.0	1.10	1.40	0.750	0.650	[16, 17]
T 2	155.0	10.0	1.20	1.30	0.700	0.650	[16, 17]
T 3	100.0	14.0	1.07	1.70	0.854	0.730	[14]
T 4	100.0	14.0	1.07	1.45	0.854	0.900	
T 5	98.6	12.1	1.07	1.50	0.647	0.925	
T 6	134.3	21.9	1.25	1.51	0.741	0.456	
T 7	150.0	14.0	1.07	1.45	0.854	0.900	
T 8	154.8	24.3	1.09	1.27	0.848	0.463	

used. This limits the validity of the extracted optical potential to the triton energy of ~9—10 MeV.

The analysed triton optical potentials are collected in Table 2 and the corresponding DWBA angular distributions are presented on Fig. 3—5, together with the experimental ones. Here, the potentials T 1—T 3 are that used by Jaskola et al. [16, 17] and that used by Burke et al. [14] for the analysis of the (d, t) reaction on

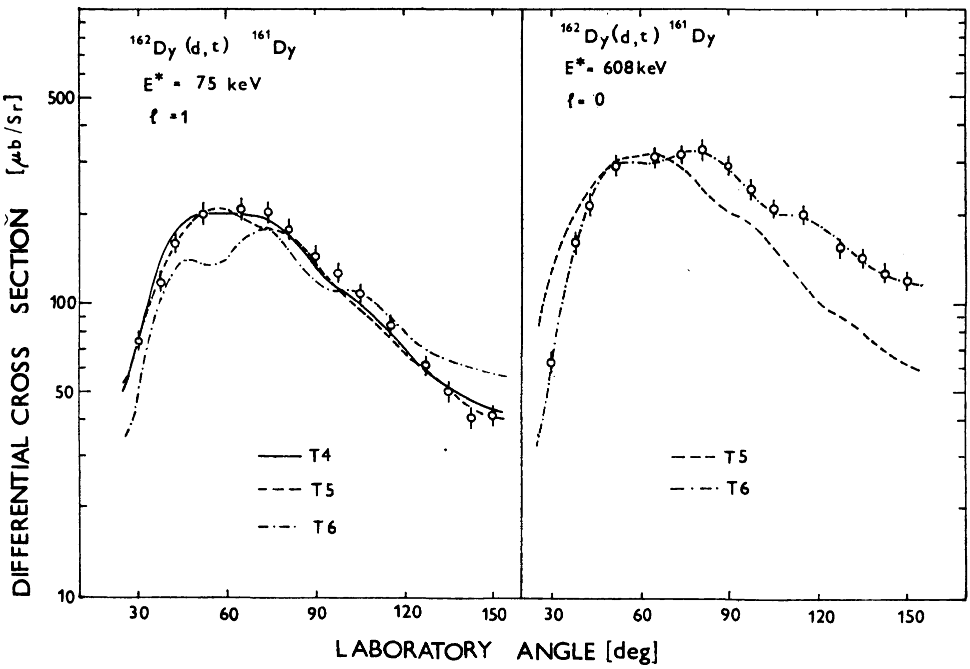

Fig. 4. The separate analysis of the angular distributions of tritons for the $l = 1$ and $l = 0$ transitions (see text and table 2.)

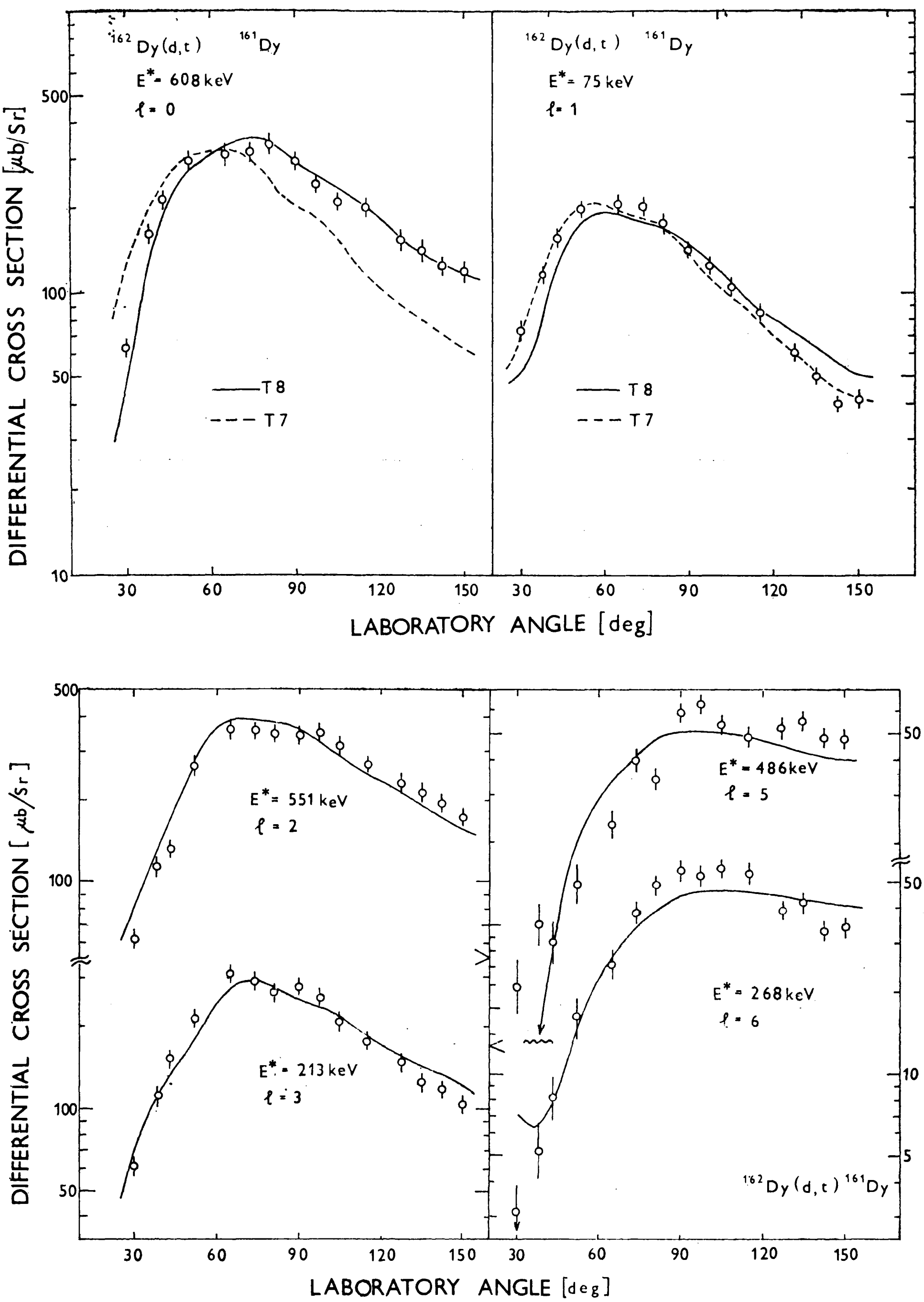

Fig. 5. The simultaneous analysis of triton angular distributions for all observed angular momenta, l. (See text and table 2.)
a) Angular distributions for $l = 0$ and $l = 1$; b) Angular distributions for $l = 2$, 3, 5 and 6

some rare earth deformed nuclei. It is substantial that all these three potentials produce DWBA angular distributions very different from the experimental ones (Fig. 3).

The potentials $T\,4$ and $T\,7$, differing only by real part, were found by trial as fitting approximately the angular distributions for the $l = 1$ transition. They were used as the starting sets in the optimalization procedure, which saved the computation time essentially.

The analysis showed that it is impossible to fit the parameters of the triton optical potential to the angular distribution of some fixed l-value only. Although the fit for the fixed angular momentum, l, was very good, the angular distributions, calculated with resulting parameters for other l-values differ strongly from the experimental ones. An example of situation is seen in Fig. 4, where the results for the potentials $T\,5$ (fitted to the $l = 1$) and $T\,6$ (fitted to the $l = 0$ transition) are presented.

To eliminate this disagreement, the optimalization program was changed and the angular distributions for all angular momenta observed, l, ($l = 0, 1, 2, 3, 5, 6$) were fitted simultaneously. As a result, the triton optical potential $T\,8$ was obtained. As is seen from Fig. 5, the DWBA angular distributions, calculated with this potential for all observed l-values agree reasonably well with the experimental ones. This indicates that the potential $T\,8$ is rather realistic and reflects at least some substantial properties of the triton potential. Therefore it is possible to use the potential $T\,8$ for the analysis of other transitions in the ^{162}Dy$(d, t)\,^{161}$Dy reaction, as it was done in paper [3].

4. Conclusion

The analysis presented in this paper showed that the study of the (d, p) and (d, t) reaction angular distributions by the DWBA method can bring valuable informations about the deuteron and triton optical potentials. For deuterons, the (d, p) reaction permitted to find the optical potential, describing simultaneously the elastic scattering as well as the single particle transfer reactions. It is remarkable that the nuclear reactions studied in the present work require rather deep potentials with strong surface absorption for deuterons as well as for tritons.

The optical potentials obtained in the present work differ, to some extent, from the "average" ones, used by other authors [6—7, 12—17]. Nevertheless, the optical potentials established for special nucleus (^{162}Dy and ^{161}Dy in our work) should reflect the differences in the nuclear structure of individual nuclei, which are well known from nuclear spectroscopy (see e.g. [18]). On the other hand, the results might be affected, to some extent, by approximate validity of the DWBA method, used in the analysis. Nevertheless, this disadvantage was partially reduced for both reactions by use of only the strongest transitions for individual angular momenta, l, for which the DWBA theory is expected to be a good approximation.

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