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CCBA CALCULATION FOR THE ^{154}Sm(d,p) ^{155}Sm REACTION AT E_d =12MEV

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Анализ реакций $^{154}Sm(d,p)^{155}Sm$ при E_d = 12 МэВ методом связанных каналов

Метод связанных каналов в борновском приближении (CCBA) применяется для описания дейтонного срыва на ^{154}Sm. Волновая функция деформированного потенциала вычисляется с помощью разложения по функциям Штурма. Параметры оптического потенциала найдены из обработки экспериментальных данных по упругому и неупругому рассеянию методом связанных каналов.

Большинство теоретически вычисленных угловых распределений находятся в хорошем согласии с экспериментальными данными.

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CCBA Calculation for the $^{154}Sm(d,p)^{155}Sm$ Reaction at E_d = 12 MeV

The coupled channel Born approximation (CCBA) is applied to the description of the deuteron stripping on ^{154}Sm using deformed bound state wave functions which are expanded in terms of Sturmian functions. The optical parameters have been adjusted by coupled channel calculations from elastic and inelastic scattering data. Most of the theoretically predicted angular distributions for the available transfers are in good agreement with the experimentally observed ones.

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1. Introduction

Recently some works have been published where inelastic processes arising in one- and two-nucleon transfer reactions have been successfully investigated and described by means of the coupled channel Born approximation (CCBA) (see, for example, ref. /1/).

It is usually believed that multi-step (i.e. inelastic) processes are important only for transitions which are forbidden to occur by a one-step process. However, as has been shown (see, e.g., ref. /2/) the multi-step processes can sometimes be very important even for transitions that are allowed to occur by one-step processes. To confirm this we apply the CCBA to the description of the deuteron stripping on the deformed nucleus ^{154}Sm. The CCBA method used is the same as employed in ref. /2/ (see also the references quoted therein) and exhibits the following particularities:

i) The generalized distorted waves are calculated by a coupled channel procedure making use of the adiabatic approximation, and therefore all rotational excitations belonging to the ground state band of the target and product nucleus have been included.

ii) The tail of the deformed bound state function of the transferred neutron is calculated with high accuracy making use of the Sturmian function expansion.

The aim of the present work is to show how well it is possible to describe the experimental data by means of such an extended CCBA method. Therefore we will not report again on a comparison between the DWBA and the CCBA calculations, because now it seems to be well understood in which cases the relatively simple DWBA fails.

We consider that the CCBA is well known and therefore, after a short information about the experiment given in the next section we will compare the experimentally observed cross sections with those predicted by the CCBA in sect. 3. Concluding remarks can be found in sect. 4.

2. Experiment

Evaporated samarium target isotopically enriched up to 95% in ^{154}Sm was bombarded with 12.1 MeV deuterons from the Niels Bohr Institute EN tandem accelerator. The target thickness was approximately 150 $\mu g/cm^2$ and evaporated onto thin carbon film. The reaction products from ^{154}Sm(d,p) and (d,t) reactions were analyzed in the single gap magnetic spectrograph /8/ and detected in an Ilford K2 emulsion. The spectra were recorded for each 5° in the interval 20° to 50° the angular range from 60° to 125° was covered in steps 15° and the extra spectrum was obtained for the angle 150°. The exposure beam charges at each angle ranged from 3000 μC to 6000 μC. The energy resolution was approximately 12÷15keV at the forward angles and slightly worse at the backward angles. The plates were scanned in 0.20 mm strips.

The absolute cross sections were determined by normalization to the cross section for elastic deuteron scattering. The values of the measured differential cross sections and the Nilsson assignments of the corresponding levels populated by the reaction are given in Table 1.

3. Comparison with the Experimental data and Discussion

Before discussing the results we should say some words about the optical and deformation parameters and about the wave function of the transferred neutron moving in a deformed orbital.

Table 1

The values of the measured differential cross sections for the ^{154}Sm(d,p)^{155}Sm reaction at E_d = 12 MeV

dσ/dΩ (μb/sr)

Peak no.	Energy (keV)	Nilsson assignment	20°	25°	30°	35°	40°	45°	50°	60°	75°	90°	105°	125°	150°
1	0	3/2 3/2-[521]	305	242	180	215	254	233	254	206	89	79	33	28	13
2	128	7/2 3/2-[521]	120	200	277	335	340	314	285	321	242	173	86	67	58
3	153	9/2 5/2+[642]	-	-	-	43	55	49	55	59	27	31	11	14	8.5
4	358	13/2 5/2+[642]	-	-	8	-	23	29	43	51	59	52	-	39	19
5	427	5/2 5/2-[523]	-	27	41	44	50	60	44	32	20	19	14	8	6.6
6	499	7/2 5/2-[523]	215	340	390	600	480	485	480	211	203	142	86	60	80
7	821	1/2 1/2-[521]	640	660	510	700	810	800	640	512	382	253	137	73	52
8	868	3/2 1/2-[521]	29	26	-	40	74	71	71	50	27	29	17	12	7
9	908	7/2 5/2-[512]	256	285	363	412	425	358	290	303	250	140	91	59	42
10	930	5/2 1/2-[521]	180	268	173	330	295	430	310	186	155	88	58	31	23
11	962	9/2 5/2-[512]	72	74	157	248	295	245	264	211	173	122	72	57	41
12	1080	7/2 1/2-[521]	-	60	75	107	116	125	112	116	95	51	52	40	39

3.1. The Optical and Deformation Parameters

The optical and deformation parameters for the exit channel have been taken from ref. /3/, where the experimental data on 12 MeV protons scattered elastically and inelastically by $^{148,154}Sm$ have been analyzed by means of a coupled channel program. For the entrance channel an extensive, though not exhaustive, search has been made for the optical and deformation parameters exploiting the experimental data of elastic and inelastic scattering of 12 MeV deuterons on ^{154}Sm of ref. /4/. The optical parameters obtained for both channels are collected in Table 2 and, as can be seen, the same deformation parameters as utilized in the proton scattering have been taken as fixed parameters in the coupled channel calculations for the deuteron scattering.

3.2. The Deformed Bound State Wave Function

The deformed bound state wave function $\Psi_{\Omega,\pi}(\vec{r})$ of the transferred neutron labelled by the projection Ω of the total angular momentum and the parity π is written as /2/

$$\Psi_{\Omega,\pi}(\vec{r}) = \sum_{n\ell j} a^{(\Omega)}_{n\ell j} \frac{S_{n\ell j}(r)}{r} \, |\, \ell j \Omega > , \qquad (1)$$

where the Sturmian functions are calculated by the following equation:

$$\left[\frac{\hbar^2}{2m}\left(\frac{d^2}{dr^2} - \frac{\ell(\ell+1)}{r^2}\right) + E_n - V_{so}(r)\vec{\ell}\cdot\vec{\sigma} - a_{n\ell j} V(r)\right] S_{n\ell j}(r) = 0 \, . \qquad (2)$$

Here $V(r)$ and $V_{so}(r)$ are the usual Saxon-Woods and spin-orbital potentials, respectively, and the coefficients $a_{n\ell j}$ are the eigenvalues of the equation. The energy E_n is the prescribed binding energy of the transferred neutron. The expansion in terms of Sturmian functions guarantees

Table 2

The optical and deformation parameters used in the CCBA calculation

Particles	V [MeV]	W_D [MeV]	r_V [fm]	r_{WD} [fm]	r_c [fm]	a_V [fm]	a_{WD} [fm]	V_{SO} [MeV]	β_2	β_4
d	98.3	7.01	1.15	1.43	1.25	0.87	0.85		0.284	0.046
p	56.69	8.62	1.204	1.243	1.204	0.741	0.629		0.284	0.046
n				1.204		0.741		12.0	0.284	0.046

that also the tail of the deformed bound state wave function is calculated within a high accuracy and decays for large distances r with the correct asymptotics. Therefore, in some sense our method is adequate to the well-known WDP method used in calculations of form factors for the transfer on spherical nuclei. Calculating the expansion coefficients for the needed deformed bound state wave function (see Table 3) the same values of the deformation parameters β_2 and β_4 as adjusted from the inelastic scattering data and given in Table 2, have been taken.

3.3. The Theoretical and Experimental Cross Sections for the Reaction $^{154}Sm(d,p)^{155}Sm$ at $E_d = 12$ MeV

Before discussing in detail some special transfers we should emphasize that when calculating the theoretical cross sections there are no free parameters which might be changed in order to improve the agreement with the experimental data. Therefore, because all needed parameters have been determined before starting the cross section calculations, the theoretically predicted cross sections displayed in Figs. 1 and 2 are not normalized to the experimental data *. As is mentioned above, the structure of the states populated at the (d,p) reaction has been considered as pure rotational one. Actually, the structure of these states is much more complicated. This concerns mainly the highly excited states. To understand their nature we show in Table 4 the results of Soloviev's semimicroscopic model /5/, where these states have been investigated on the basis of the quasiparticle-phonon interaction.

The $3/2^-[521]$ ground state band

As can be seen the agreement between theory and experiment is satisfactory. Taking into account the quasiparticle character of the states the theoretically predicted cross sections must be multiplied by a factor of 0.701.

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* In agreement with the finite-range theory the calculated cross sections have been multiplied by the compromize factor 1.5.

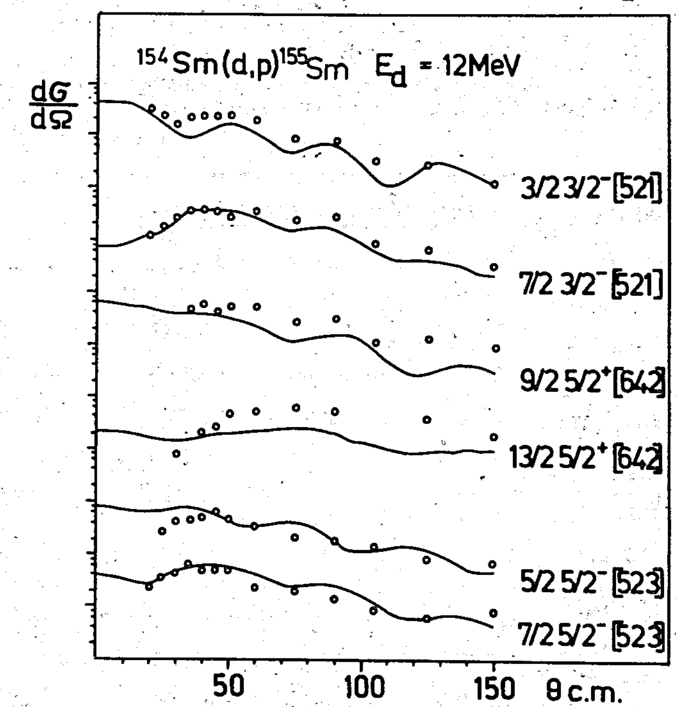

Fig. 1. The CCBA calculation compared with the available experimental data of the reaction $^{154}Sm(d,p)^{155}Sm$ (the absolute values of the cross sections can be obtained using the values of Table 1).

The $5/2^+[642]$ band

In the transfer to states of the $5/2^+[642]$ band cross sections have been measured belonging to relatively high spins. Note, that DWBA yields for these two transfers cross sections which are too small and whose shape at the forward angles does not agree with the experimentally observed one.

Couplings of various types tend to obscure the simple picture of the excitation in deformed nuclei provided by the transfer reactions. Probably, the Coriolis coupling is the most important and best understood phenomenon which gives rise to intermixing of the one particle wave functions. Coupled channel calculations have shown /6/

Table 3
The Sturm-Liouville expansion coefficients for the deformed bound state wave functions

Band	basic states	Sturm-Liouville coefficients			
		N = 1	N = 3	N = 5	N = 7
$\frac{3}{2}^-[521]$	$p_{3/2}$	-0.043	-0.II5	0.344	0.035
	$f_{5/2}$		0.006	-0.266	-0.046
	$f_{7/2}$		0.007	0.799	0.045
	$h_{9/2}$			0.I65	-0.058
	$h_{11/2}$			-0.3I3	0.I23
	$j_{13/2}$				0.04I
	$j_{15/2}$				-0.046
$\frac{1}{2}^-[521]$	$p_{1/2}$	0.025	0.065	-0.500	-0.036
	$p_{3/2}$	0.002	0	0.308	0.007
	$f_{5/2}$		-0.06I	-0.I09	-0.059
	$f_{7/2}$		-0.042	-0.5I4	0.03I
	$h_{9/2}$			0.494	0.009
	$h_{11/2}$			0.255	-0.095
	$j_{13/2}$				0.I03
	$j_{15/2}$				0.035

Table 3 (continuation)

Band	basic states	Sturm-Liouville expansion coefficients			
		N = 3	N = 5	N = 7	N = 9
$\frac{5}{2}^-[523]$	$f_{5/2}$	0.055	-0.279	-0.024	-0.007
	$f_{7/2}$	0.043	0.770	-0.033	-0.007
	$h_{9/2}$		-0.361	-0.060	0.016
	$h_{11/2}$		-0.407	0.120	0.029
	$j_{13/2}$			-0.055	-0.021
	$j_{15/2}$			-0.047	0.001
	$l_{17/2}$				-0.007
$\frac{5}{2}^-[512]$	$f_{5/2}$	-0.070	0.161	0.027	0.014
	$f_{7/2}$	0.083	0.467	0.028	0.001
	$h_{9/2}$		0.815	0.003	0.002
	$h_{11/2}$		0.051	0.058	0.019
	$j_{13/2}$			0.151	0.042
	$j_{15/2}$			0.005	0.001
	$l_{17/2}$				0.020

Band	basic states	Sturm-Liouville coefficients			
		N = 2	N = 4	N = 6	N = 8
$\frac{5}{2}^+[642]$	$d_{5/2}$	-0.014	-0.063	0.072	0.018
	$g_{7/2}$		0.030	-0.038	-0.016
	$g_{9/2}$		-0.198	0.379	0.062
	$i_{11/2}$			-0.076	-0.035
	$i_{13/2}$			0.820	0.074
	$k_{15/2}$				-0.034
	$k_{17/2}$				0.135

that the Coriolis interaction must be taken into account in transfers to such even states. For these transfers the correction factor amounts to about 1.35, while the corrections due to Soloviev's model yield a factor 0.762. This means that the theoretical cross sections given in Fig. 1 remain nearly the same as drawn.

The $5/2^-[523]$ band

As can be seen the CCBA predicts for both transfers cross sections which are in rather good agreement with the experimental data. The consideration of the quasiparticle properties of the states leads to decreasing absolute cross sections by about factor of 0.83.

The $1/2^-[521]$ band

As can be seen from Table 4 the structure of $1/2^-[521]$ states is rather complicated. There are admixtures of the $1/2^-[530]$ state as well as those arising from the quasiparticle-phonon interaction. Transfers to these states should be described taking into account the nonrotational levels from the very beginning as has been done in ref. /7/. Such calculations are rather tedious and therefore we restrict ourselves to qualitative discussions basing on the more simple calculations. We see that for the first two states the CCBA predicts in some measure the experimentally observed cross sections. The strong undulation of the $3/2^-$ states has been caused by a strong interference between the 3p1/2 and 3p3/2 basic states (see Table 2) in the transfer amplitude. It could be abolished by a small variation of the potential parameters when calculating the deformed bound state wave function. The DWBA predicts for the $3/2^-$ state an absolute cross section which is about a factor of 2.5 smaller than that of the $1/2^-$ state. Note, that the CCBA yields the experimentally observed difference (about factor of 10) for the absolute cross sections of these two states rather well.

The transfer to the next state ($J = 5/2^-$) would be in the DWBA nearly stripping forbidden ($(a_{2f5/2})^2 \approx 0.01$) and the CCBA predicts absolute cross sections still about a factor of 10 smaller than the experimental ones. Maybe,

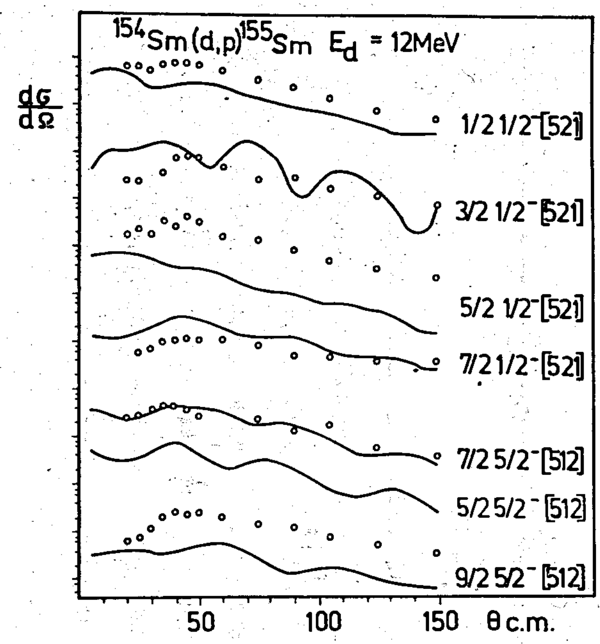

Fig. 2. The CCBA calculation compared with the available experimental data of the reaction $^{154}Sm(d,p)^{155}Sm$ (the absolute values of the cross sections can be obtained using the values of Table 1).

the level ordering proposed is not correct. For the $J=7/2^-$ state the calculated cross section is in rather good agreement with the experimental data.

The $5/2^-[512]$ band

From Table 3 it can be seen, that the structure of the states belonging to the $5/2^-[512]$ rotational band is rather complicated. Therefore, our simple CCBA treatment can hardly describe the real transfer processes. The measured cross section belonging to the peak 9 (E_x = 908 keV) is rather large and therefore it is hard to assume that this is the cross section leading to the ground state of the $5/2^-[512]$ band. Using the simple DWBA the absolute cross sections for this state should be about a factor of 9 smaller than that to the next $7/2^-$ states ($a^2_{2f7/2}$ /

Table 4
The structure of the first non-rotational states of ^{155}Sm as given in ref. 7.

K	ENERGY [keV]	STRUCTURE
$3/2^-$	0	$521\uparrow$ 93%; $521\downarrow + Q_1(22)$ 2%
$5/2^+$	90	$642\uparrow$ 94%; $523\downarrow + Q_1(30)$ 1%
$5/2^-$	310	$523\downarrow$ 90%; $512\uparrow$ 2%; $521\downarrow + Q_1(22)$ 3%; $642\uparrow + Q_1(30)$ 2%
$1/2^-$	810	$521\downarrow$ 66%; $530\uparrow$ 5%; $521\uparrow + Q_1(22)$ 15%; $523\downarrow + Q_1(22)$ 10%
$5/2^-$	1220	$512\uparrow$ 45%; $523\downarrow$ 5%; $642\uparrow + Q_1(30)$ 42%; $510\uparrow + Q_1(22)$ 2%

$/a^2_{2f5/2} \approx 9$). The Fig. 2 shows the calculated two cross sections for $J = 5/2$ and $J = 7/2$, respectively. We see that the $J = 7/2$ cross section agrees well with the experimental data and therefore it could be assigned as given in Table 1. The cross section belonging to the peak 11 ($E_x = 962$ keV) can probably not be explained assuming a $9/2\ 5/2^-[512]$ state. The theoretical cross sections become too small (see Fig. 2).

In order to obtain certain structural information about this state a more consistent coupled channel calculation should be performed including the strong admixtures due to the quasiparticle-phonon interaction.

4. Conclusion

The results obtained in the present work show how profitable is the CCBA method in describing transfer reactions which take place via inelastic excitations. To obtain reasonable results, a series of properties of the special considered nuclei should be previously well known and, if possible, complete. The comparison with the experimental cross section gives then an answer to the question whether our conception concerning the nuclear stricture involved, is correct or not. In this sense the CCBA differs from the DWBA, where spectroscopic information has been obtained after the comparison of the calculated cross sections with the experimental data.

The results indicate rather clearly that the CCBA as used here fails to describe the corresponding transfers to highly excited states. In these cases there should be taken into account still more channels and the complicated structure of the populated states. At present such an intension seems to be far from its realization.

Taking into account the quasiparticle structure of the populated levels, the theoretically predicted cross sections become systematically too small in comparison with the experimentally observed ones.

The account of the Coriolis interaction increases the cross sections by about 30%.

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References

1. S.K.Penny and G.R.Satchler. Nucl.Phys., 53, 154 (1964).
   P.J.Iano and N.Austern. Phys.Rev., 151, 853 (1966).
   R.H.Siemssen and J.R.Erskine. Phys.Rev., 146, 911 (1966).
   B.Kozlowsky and A. de-Shalit. Nucl.Phys., 77, 215(1966).
   F.S.Levin. Phys.Rev., 147, 715 (1966).
   H.Schulz and H.J.Wiebicke. Phys.Lett., 29B, 18 (1969).
   T.Tamura, D.R.Bes, R.A.Broglia and S.Landowne. Phys.Rev.Lett., 25, 1507 (1970).
   N.K.Glendenning and R.S.Mackintosh. Nucl.Phys., A168, 575 (1971).
   H.Schulz, H.J.Wiebicke, R.Fülle, D.Netzband and K.Schlott. Nucl.Phys., A159, 324 (1970).
   D.Braunschweig, T.Tamura and T. Udagawa. Phys.Lett., 35B, 273 (1971).
   R.J.Ascuitto, C.H.King and L.J.McVay. Phys.Rev.Lett., 29, 1106 (1972).
2. H.Schulz, H.J.Wiebicke and F.A.Gareev. Nucl.Phys., A180, 625 (1972).
   H.J.Wiebicke, V.K.Lukyanov and H.Schulz. Particles and Nucleus, v. 3, 993 (1972).
3. A.B.Kurepin, H.Schulz and H.J.Wiebicke. Nucl.Phys., A189, 257 (1972).
4. A.B.Kurepin. Izv. Akad. Nauk, SSSR, ser.fiz., 32, 1946 (1968).
5. V.G.Soloviev. "Teoriya slozhnykh yader", Nauka, 1971.
   F.A.Gareev, S.P.Ivanova, V.G.Soloviev and S.I.Fedotov. Particle and Nucleus, v. 4, 357 (1973).
6. F.A.Gareev, M.Baznat, H.J.Wiebicke and H.Schulz. Yad.Fiz., v. 17, 761 (1973).
7. O.Dumitrescu, V.K.Lukyanov, I.Z.Petkov, H.J.Wiebicke and H.Schulz. Nucl.Phys., A149, 253 (1970).
8. J.Borggreen, B.Elbek and L.Perch Nielsen. Nucl. Instr. Meth., 24, 1 (1961).

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