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Author: Kwaśniewicz Edward, Jan Kisiel

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SPECTROSCOPIC AMPLITUDES FOR THE TWO-NUCLEON TRANSFER BETWEEN EXCITED STATES OF 1p-SHELL NUCLEI*

By E. Kwaśniewicz

Institute of Physics, Silesian Technical University, Katowice**

and J. Kisiel

Institute of Physics, Silesian University, Katowice***

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Spectroscopic amplitudes are calculated for a transfer of two nucleons in the $(S, T = 1.0)$ and (0,1) states between low-lying, normal parity states of 1p-shell nuclei. Calculations are performed with the intermediate-coupling model wavefunctions of nuclei considered. The wavefunctions were generated using the interaction parameters of Cohen and Kurath. These spectroscopic amplitudes are necessary for a description of two-nucleon transfer in one of intermediate steps of the multi-step sequential transfer process. Sum rules for the calculated spectroscopic amplitudes are given.

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1. Introduction

Spectroscopic amplitudes (SAs) are indispensable in many studies on nuclear structure, in particular in analyzing the mechanism of various reactions involving a few-nucleon transfers.

The mechanism of some transfer reactions, e.g. the reactions concerning a transfer of particles like ^{4}H [1], ^{5}He/^{5}Li [2–5] or ^{6}He/^{6}Li [4] comprises processes more sophisticated than the one-step direct transfer processes. The results of some papers published recently [1, 6–8] show the important role of two- and/or more than two-step direct sequential transfer processes in a description of the mechanism of some few-nucleon transfer reactions. However, for the investigation of these processes a knowledge of spectroscopic amplitudes is required for the N, 2N, t/^{3}He, α-particle, etc. transfer between excited states of inter-

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** Address: Instytut Fizyki, Politechnika Śląska, Krasińskiego 8, 40-019 Katowice, Poland.

*** Address: Instytut Fizyki, Uniwersytet Śląski, Uniwersytecka 4, 40-007 Katowice, Poland.

mediate nuclei induced by the multi-step sequential processes. For this purpose, SAs for a nucleon [9] and α-particle [10] transfer between excited states of 1p-shell nuclei have been calculated recently. These data together with the results of Kurath et al. [11–14] and Kwaśniewicz et al. [15–16] offer a rather extensive collection of SAs for studying many multi-step processes in 1p-shell nuclei.

The aim of the present work is to extend the above collection of SAs to the case of the transfer of two nucleons in the (S, T = 1, 0) and (0, 1) states (in what follows denoted as 2N transfer) between low-lying, normal parity states of 1p-shell nuclei. These two-nucleon SAs together with the SAs of Ref. [12] provide a wide set of data for a description of the transition of 2N between several intermediate states of the multi-step sequential transfer process which can contribute to the mechanism of some few-nucleon transfer reactions in 1p-shell nuclei.

The wavefunctions used in the present calculations as well as in our earlier papers on SAs for 1p-shell nuclei [9, 10, 15, 16] are the intermediate-coupling model wavefunctions obtained with the interaction parameters of Cohen and Kurath [17].

A method of calculating 2N spectroscopic amplitudes for the low-lying, normal parity states of 1p-shell nuclei is shortly presented in Section 2. In Section 3 sum rules for calculated SAs are derived. The example of their application for predicting the contribution of any allowed intermediate state to 2N transfer in one of intermediate steps of multi-step sequential transfer process is presented.

2. *Method of calculations*

The definition of spectroscopic amplitudes (SAs) for partition of a given nucleus A into the core nucleus B and the cluster C one can find in many papers (see, e.g., [18, 19, 15, 16]). According to the notation of Refs [15, 16] the SAs for decomposition of the nucleus A into the core nucleus B and light cluster C in the state $|\varphi_{nL}(\vec{R}_{BC})\rangle$ (n is the number of nodes, excluding those at 0 and ∞, and L is the angular momentum) of their relative motion can be defined as follows

$$S_{nLJ} = \binom{A}{C}^{\frac{1}{2}} \langle \phi^A_{E_A J_A T_A} | (\phi^B_{E_B J_B T_B} \times (\varphi_{nL}(\vec{R_{BC}}) \times \phi^C_{E_C J_C T_C})^{JT_C})^{J_A T_A} \rangle, \tag{1}$$

where $\phi_{E_i J_i T_i}$ is the antisymmetric, intrinsic wavefunction of nucleus i ($i = A, B$ or C) labelled by the energy E_i, spin J_i and isospin T_i. The order of coupling of angular momenta is shown by the parentheses.

The explicit expression for calculating the SAs defined by (1) depends on the model involved to generate the nuclear wavefunctions. It has been displayed in many papers that a lot of low-lying states of 1p-shell nuclei can be satisfactorily described well in the framework of the shell model presuming for the motion of nucleons a space restricted to the $(1s)^4(1p)^n$ shell-model configuration only. Therefore the wavefunctions of these states can be expanded in the harmonic-oscillator basis

$$\{|s^4 p^n [f] \alpha LS; JT\rangle\}, \tag{2}$$

where $[f]$ is the Young scheme determining the permutational symmetry of the orbital part of the state, $L(S)$ is the total orbital angular momentum (spin) of the state, $J(T)$ is the total spin (isospin) of a nucleus (the order of angular momenta coupling in this paper is: $\vec{J} = \vec{L} + \vec{S}$), and α defines a set of additional quantum numbers required for a complete labelling of the state.

Expanding the wavefunctions of the nuclei A and B in the basis (2) and following the steps of Section 2 of Ref. [15] Eq. (1) takes the form

$$S_{nLJ} = \binom{A}{C}^{\frac{1}{2}} \left(\frac{A}{A-C}\right)^{\frac{2n+L}{2}} \sum_{i,j} c(i)c(j) \langle \psi(s^4 p^{A-4}[f_i]\alpha_i L_i S_i; J_A T_A)| \\ |(\psi(s^4 p^{B-4}[f_j]\alpha_j L_j S_j; J_B T_B) \times (\varphi_{nL}(\vec{R_C}) \times \phi^C_{E_C J_C T_C})^{JT_C})^{J_A T_A}\rangle, \tag{3}$$

where $c(i)$ and $c(j)$ are the expansion coefficients of the wavefunctions of nuclei A and B.

In what follows the SAs will be considered for 2N transfer between low-lying, normal parity states of 1p-shell nuclei. Making use of the two-nucleon coefficients of fractional parentage (c.f.p.) for the 1p shell [20] the bra state of Eq. (3) can be expressed as a product of the $|\psi(s^4 p^{B-4})\rangle$ and $|\psi(p^2)\rangle$ states. Thus, the overlap on the right-hand side of Eq. (3) reads

$$\langle \psi(s^4 p^{A-4} \ldots)|(\psi(s^4 p^{B-4} \ldots) \times (\varphi_{nL}(\vec{R_C}) \times \phi^C(s^2[2]S_C T_C))^{JT_C})^{J_A T_A}\rangle \\ = \binom{A}{4}^{-\frac{1}{2}} \binom{A-2}{4}^{\frac{1}{2}} \hat{L}_i \hat{S}_i \hat{J}_B \hat{J} \begin{Bmatrix} L_j & S_j & J_B \\ L & S_C & J \\ L_i & S_i & J_A \end{Bmatrix} \\ \times \langle p^{A-4}[f_{pi}]\alpha_i L_i T_A S_i | p^{B-4}[f_{pj}]\alpha_j L_j T_B S_j, p^2[2] L T_C S_C\rangle \\ \times \langle p^2[2] L S_C; J T_C | (\varphi_{nL}(\vec{R_C}) \times \phi^C(s^2[2]S_C T_C))^{JT_C}\rangle, \tag{4}$$

where $\langle p^{A-4} | p^{B-4}, p^2\rangle$ is a two-nucleon c.f.p. for the 1p-shell [20] and $[f_{pi}]$ and $[f_{pj}]$ are the counterparts of the diagrams $[f_i]$ and $[f_j]$ corresponding to 1p-shell nucleons only, $\{::::::::\}$ is the $9j$ coefficient for recoupling of angular momenta, and $\hat{L} = \sqrt{2L+1}$. The second overlap on the right-hand side of Eq. (4) is equal to $\sqrt{2}/2$ (of course, on the condition that $\varphi_{nL}(\vec{R_C})$ is approximated by the harmonic oscillator wavefunction with the same oscillator size parameter as for nuclei A, B and particle C[1]). So, due to this fact and taking into account (4) Eq. (3) becomes

$$S_{nLJ} = \frac{\sqrt{2}}{2} \binom{A-4}{2}^{\frac{1}{2}} \left(\frac{A}{A-2}\right)^{\frac{2n+L}{2}} \sum_{i,j} C(i)C(j) \\ \times \hat{L}_i \hat{S}_i \hat{J}_B \hat{J} \begin{Bmatrix} L_j & S_j & J_B \\ L & S_C & J \\ L_i & S_i & J_A \end{Bmatrix} \\ \times \langle p^{A-4}[f_{pi}]\alpha_i L_i T_A S_i | p^{B-4}[f_{pj}]\alpha_j L_j T_B S_j, p^2[2] L T_C S_C\rangle. \tag{5}$$

[1] The quantum numbers n and L result from the expression $Q_A - Q_B = 2n+L$ ($n = 0, 1, 2, \ldots$), where Q_A and Q_B are numbers of oscillator quanta for nuclei A and B, respectively.

The 2N SAs were calculated for low-lying states of 1p-shell nuclei according to Eq. (5) with the aid of program AMPL [21]. The necessary two-nucleon c.f.p. were taken from Ref. [20]. The wavefunctions used in the present calculations are the same as those used in our earlier papers on the SAs for 1p-shell nuclei [9, 10, 15, 16]. In order to check the used program the 2N SAs for the nuclear states of Ref. [12] were recalculated[2]. The results of the present calculations are given in Tables I and II. For the users' convenience the 2N SAs for the most states of Ref. [12] are collected in Tables I and II as well[3].

3. Sum rules and their application for predicting the intermediate states contribution to two--nucleon transfer

The sum rules for 2N pickup and stripping can be obtained by the straightforward adaptation of the sum rules of Ref. [13]. These sum rules can also be derived with the help of the orthonormality relations obeyed by the: (*i*) c.f.p. entering into the formula (5); (*ii*) expansion coefficients c of the appropriate nuclear states; (*iii*) 9j coefficients for recoupling of angular momenta. The pickup sum rule for the SAs of Eq. (5) is

$$\sum_{J_B T_B E_B L J} (S_{nLJ})^2 = \frac{A^2}{2(A-2)^2} \binom{A-4}{2} \sum_i \frac{c^2(i)}{\dim [f_{pi}]} \sum_{[f_0]} \dim [f_0], \tag{6}$$

where $c(i)$ are the expansion coefficients of the wavefunction of the target nucleus A and $\dim [f]$ is the dimension of the representation $[f]$ of the permutation group S_n of n particles. The second sum on the right-hand side includes all $[f_0]$ for which $[f_{pi}]$ appears in the pro-

[2] The transformation of the SAs from the $(j_1 j_2)$ representation of Ref. [12] to the LS representation (Eq. (5) of present work) is given by the equation

$$S_{nLJ} = \frac{\sqrt{2}}{2} \left(\frac{A}{A-2} \right)^{\frac{2n+L}{2}} \left(\frac{A-4}{2} \right)^{\frac{1}{2}} \mathscr{S}_{nLJ},$$

where for two nucleons in the $(S, T = 1,0)$ state

$$\mathscr{S}_{101} = \sqrt{\tfrac{10}{27}}\, Q^{10}(33) - \sqrt{\tfrac{16}{27}}\, Q^{10}(31) - \sqrt{\tfrac{1}{27}}\, Q^{10}(11),$$

$$\mathscr{S}_{021} = -\sqrt{\tfrac{2}{27}}\, Q^{10}(33) - \sqrt{\tfrac{5}{27}}\, Q^{10}(31) + \sqrt{\tfrac{20}{27}}\, Q^{10}(11),$$

$$\mathscr{S}_{022} = Q^{20}(31),$$

$$\mathscr{S}_{023} = Q^{30}(33),$$

and for two nucleons in the $(S, T = 0,1)$ state

$$\mathscr{S}_{100} = \sqrt{\tfrac{2}{3}}\, Q^{01}(33) + \sqrt{\tfrac{1}{3}}\, Q^{01}(11),$$

$$\mathscr{S}_{022} = \sqrt{\tfrac{1}{3}}\, Q^{21}(33) + \sqrt{\tfrac{2}{3}}\, Q^{21}(31).$$

The $Q^{JT}(2j_1, 2j_2)$ symbols represent the 2c.f.p. from Tables I and II of Ref. [12].

[3] The phases of some SAs of the present work are opposite to those of the appropriate SAs of Ref. [12]. This is implied by the method of the present calculations based on the c.f.p. of Refs [20, 24].

TABLE I

Spectroscopic amplitudes for the transfer of two nucleons in the ($S, T = 1,0$) state between normal parity states of 1p-shell nuclei. The states of the nucleus $A(B)$ specified by spin J, isospin T and calculated excitation energy E_{calc} (in MeV) are in the first (second) three columns, respectively. The orbitals of the transferred particle are in the last four columns

B = 5			A = 7			S_1	D_1	D_2	D_3
J	T	E_{calc}	J	T	E_{calc}				
1/2	1/2	0.4	1/2	1/2	1.07	0.337	-0.464	-	-
			3/2	1/2	0.00	-0.523	-0.109	0.360	-
					10.87	-0.463	-0.141	0.138	-
			5/2	1/2	7.40	-	-	-0.428	-0.421
					9.15	-	-	0.112	-0.545
			7/2	1/2	4.79	-	-	-	0.639
3/2	1/2	0.00	1/2	1/2	1.07	-0.881	-0.230	-0.549	-
			3/2	1/2	0.00	0.690	-0.057	-0.031	0.737
					10.87	-0.540	-0.688	0.629	0.038
			5/2	1/2	7.40	0.252	0.790	0.638	0.108
					9.15	0.702	-0.176	-0.199	-0.724
			7/2	1/2	4.79	-	-	-0.452	-0.926

B = 6			A = 8			S_1	D_1	D_2	D_3
J	T	E_{calc}	J	T	E_{calc}				
1	0	0.00	0	0	0.00	1.146	0.112	-	-
			1	0	14.98	-0.055	0.030	0.265	-
			2	0	3.41	0.089	0.414	0.477	0.744
			4	0	11.29	-	-	-	0.126
1	0	5.06	0	0	0.00	-0.327	0.372	-	-
			1	0	14.98	-0.056	-0.014	0.433	-
			2	0	3.41	0.371	0.053	-0.356	-0.130
			4	0	11.29	-	-	-	0.605
2	0	5.23	0	0	0.00	-	-	0.602	-
			1	0	14.98	0.114	0.473	$<$0.001	0.806
			2	0	3.41	-0.556	0.209	0.248	-0.259
			4	0	11.29	-	-	-0.465	-0.721
3	0	2.14	0	0	0.00	-	-	-	0.850
			1	0	14.98	-	-	0.806	$<$0.001
			2	0	3.41	0.747	0.079	0.259	0.538
			4	0	11.29	-0.036	0.626	0.721	0.751
0	1	2.51	1	1	16.88	0.106	-0.091	-	-
			2	1	15.80	-	-	-0.085	-
			3	1	17.49	-	-	-	-0.685
2	1	6.04	1	1	16.88	0.307	0.372	-0.248	-0.594
			2	1	15.80	0.330	-0.155	0.398	-0.833
			3	1	17.49	0.555	-0.040	0.034	0.362

B = 7			A = 9			S_1	D_1	D_2	D_3
J	T	E_{calc}	J	T	E_{calc}				
1/2	1/2	1.07	1/2	1/2	2.99	-0.187	-0.471	-	-
			3/2	1/2	0.00	-0.252	0.174	-0.323	-
					5.07	0.139	0.277	0.006	-
			5/2	1/2	2.63	-	-	-0.243	0.354
			7/2	1/2	6.19	-	-	-	0.255
3/2	1/2	0.00	1/2	1/2	2.99	-0.114	0.154	0.548	-
			3/2	1/2	0.00	-0.155	-0.179	-0.101	0.558
					5.07	0.123	-0.184	-0.365	-0.334
			5/2	1/2	2.63	-0.109	-0.003	0.150	0.607
			7/2	1/2	6.19	-	-	0.211	0.571
3/2	1/2	10.87	1/2	1/2	2.99	-0.527	-0.033	-0.053	-
			3/2	1/2	0.00	0.445	0.171	0.168	-0.078
					5.07	0.044	-0.001	-0.096	-0.425
			5/2	1/2	2.63	0.029	0.300	0.108	-0.280
			7/2	1/2	6.19	-	-	0.247	0.436
5/2	1/2	7.40	1/2	1/2	2.99	-	-	-0.240	0.205
			3/2	1/2	0.00	0.207	0.144	-0.288	0.016
					5.07	-0.207	-0.353	-0.146	-0.060
			5/2	1/2	2.63	0.061	-0.261	0.150	-0.281
			7/2	1/2	6.19	0.428	0.109	0.086	0.191
5/2	1/2	9.15	1/2	1/2	2.99	-	-	-0.009	0.411
			3/2	1/2	0.00	0.712	-0.039	0.015	-0.519
					5.07	-0.266	0.094	-0.180	-0.409
			5/2	1/2	2.63	-0.244	-0.081	-0.483	-0.583
			7/2	1/2	6.19	-0.202	0.501	0.432	0.196
7/2	1/2	4.79	1/2	1/2	2.99	-	-	-	0.500
			3/2	1/2	0.00	-	-	-0.080	0.709
					5.07	-	-	0.501	0.395
			5/2	1/2	2.63	0.376	0.131	0.191	-0.431
			7/2	1/2	6.19	0.337	0.147	0.134	0.637

B = 8			A = 10			S_1	D_1	D_2	D_3
J	T	E_{calc}	J	T	E_{calc}				
0	0	0.00	1	0	0.90	0.758	0.162	-	-
					2.38	0.242	-0.283	-	-
					6.19	-0.084	0.483	-	-
			2	0	3.34	-	-	0.296	-
					5.53	-	-	0.482	-
			3	0	0.00	-	-	-	0.496
					4.72	-	-	-	-0.052
1	0	14.98	1	0	0.90	0.112	-0.034	-0.086	-
					2.38	-0.085	-0.053	0.259	-
					6.19	-0.261	-0.122	-0.391	-
			2	0	3.34	0.087	-0.184	0.160	-0.419
					5.53	-0.044	-0.027	-0.001	-0.126
			3	0	0.00	-	-	-0.164	0.150
					4.72	-	-	0.291	0.034
2	0	3.41	1	0	0.90	-0.240	-0.397	0.400	-0.448
					2.38	0.694	-0.181	0.038	-0.196
					6.19	0.114	-0.440	-0.631	-0.126
			2	0	3.34	-0.675	-0.303	-0.178	-0.025
					5.53	0.266	0.526	-0.563	-0.553
			3	0	0.00	0.021	-0.009	0.214	-0.866
					4.72	0.690	-0.108	0.301	-0.291
4	0	11.29	1	0	0.90	-	-	-	0.237
					2.38	-	-	-	-0.815
					6.19	-	-	-	0.092
			2	0	3.34	-	-	-0.294	0.748
					5.53	-	-	0.117	0.196
			3	0	0.00	-0.179	0.054	-0.132	0.732
					4.72	-0.016	-0.505	0.366	-0.342

B = 8			A = 10			S_1	D_1	D_2	D_3
J	T	E_{calc}	J	T	E_{calc}				
1	1	16.88	0	1	1.42	-0.373	0.187	-	-
					12.47	-0.023	0.426	-	-
			1	1	9.55	-0.150	0.341	-0.153	-
			2	1	5.58	-0.106	0.132	0.239	0.082
					7.23	0.127	-0.255	-0.074	0.187
2	1	15.80	0	1	1.42	-	-	0.172	-
					12.47	-	-	0.323	-
			1	1	9.55	-0.151	-0.056	0.448	-0.347
			2	1	5.58	-0.252	0.052	-0.007	0.659
					7.23	-0.175	-0.297	-0.494	-0.520
3	1	17.49	0	1	1.42	-	-	-	1.353
					12.47	-	-	-	0.264
			1	1	9.55	-	-	0.119	-0.086
			2	1	5.58	-0.401	-0.071	-0.337	-0.876
					7.23	0.487	-0.085	-0.148	0.006

B = 9			A = 11			S_1	D_1	D_2	D_3
J	T	E_{calc}	J	T	E_{calc}				
1/2	1/2	2.99	1/2	1/2	1.71	0.302	-0.431	-	-
					11.62	-0.397	-0.081	-	-
			3/2	1/2	0.00	0.283	0.111	-0.257	-
					5.39	0.149	0.036	-0.117	-
					11.44	0.593	0.065	-0.113	-
			5/2	1/2	4.35	-	-	-0.086	0.052
					8.11	-	-	0.120	0.448
			7/2	1/2	5.85	-	-	-	0.446
3/2	1/2	0.00	1/2	1/2	1.71	-0.801	-0.252	-0.627	-
					11.62	0.179	0.264	-0.555	-
			3/2	1/2	0.00	-0.395	0.186	0.028	-0.701
					5.39	-0.325	-0.166	0.025	-0.236
					11.44	-0.128	0.233	-0.320	0.398
			5/2	1/2	4.35	-0.267	0.137	-0.095	0.154
					8.11	-0.390	-0.325	0.004	0.044
			7/2	1/2	5.85	-	-	-0.421	-0.131
			9/2	1/2	12.73	-	-	-	-0.024
3/2	1/2	5.07	1/2	1/2	1.71	0.211	-0.026	0.085	-
					11.62	-0.231	0.377	-0.155	-
			3/2	1/2	0.00	0.233	0.118	0.025	0.003
					5.39	-0.138	-0.240	0.046	0.068
					11.44	0.100	0.140	-0.217	0.361
			5/2	1/2	4.35	-0.421	0.134	-0.276	0.036
					8.11	0.037	-0.103	0.304	-0.541
			7/2	1/2	5.85	-	-	-0.191	0.513
			9/2	1/2	12.73	-	-	-	-0.156

B = 9			A = 11			S_1	D_1	D_2	D_3
J	T	E_{calc}	J	T	E_{calc}				
5/2	1/2	2.63	1/2	1/2	1.71	-	-	0.120	-0.049
					11.62	-	-	-0.220	-0.512
			3/2	1/2	0.00	0.453	-0.170	-0.061	-0.460
					5.39	-0.680	-0.160	0.319	0.169
					11.44	0.052	0.196	-0.342	0.260
			5/2	1/2	4.35	-0.487	-0.088	-0.386	0.530
					8.11	0.335	0.329	0.006	0.374
			7/2	1/2	5.85	0.133	-0.130	0.330	0.446
			9/2	1/2	12.73	-	-	-0.147	-0.089
7/2	1/2	6.19	1/2	1/2	1.71	-	-	-	0.706
					11.62	-	-	-	0.084
			3/2	1/2	0.00	-	-	0.005	1.076
					5.39	-	-	-0.650	-0.152
					11.44	-	-	<0.001	-0.029
			5/2	1/2	4.35	0.231	0.311	0.203	-0.515
					8.11	0.113	0.116	-0.190	0.137
			7/2	1/2	5.85	0.077	0.044	0.344	0.292
			9/2	1/2	12.73	-0.232	0.441	-0.268	-0.037
1/2	3/2	16.61	1/2	3/2	13.57	0.060	0.228	-	-
			3/2	3/2	15.85	0.091	0.055	0.087	-
3/2	3/2	13.28	1/2	3/2	13.57	0.057	0.241	0.511	-
			3/2	3/2	15.85	-0.327	-0.089	0.244	0.384

A = 12			B = 10			S_1	D_1	D_2	D_3
J	T	E_{calc}	J	T	E_{calc}				
0	0	0.00	1	0	0.90	-1.090	-0.228	-	-
					2.38	-0.524	0.677	-	-
					6.19	0.026	-0.176	-	-
			2	0	3.34	-	-	-0.878	-
					5.53	-	-	-0.442	-
			3	0	0.00	-	-	-	-1.539
					4.72	-	-	-	0.895
0	0	13.45	1	0	0.90	-0.645	-0.258	-	-
					2.38	0.213	0.297	-	-
					6.19	0.270	-0.643	-	-
			2	0	3.34	-	-	-0.558	-
					5.53	-	-	-0.302	-
			3	0	0.00	-	-	-	1.012
					4.72	-	-	-	0.150
2	0	4.65	1	0	0.90	-0.016	-0.253	-0.117	-0.532
					2.38	-0.226	0.272	-0.665	0.121
					6.19	-0.310	-0.027	0.012	0.055
			2	0	3.34	-0.129	-0.565	-0.242	0.648
					5.53	0.602	-0.067	0.139	-0.100
			3	0	0.00	-0.715	-0.267	-0.449	0.150
					4.72	-0.494	0.178	0.488	0.894

A = 12			B = 10			S_1	D_1	D_2	D_3
J	T	E_{calc}	J	T	E_{calc}				
0	1	19.59	1	1	9.55	0.789	0.316	-	-
			2	1	5.58	-	-	0.580	-
					7.23	-	-	0.792	-
1	1	15.08	0	1	1.42	0.291	0.053	-	-
					12.47	0.277	0.120	-	-
			1	1	9.55	0.236	-0.266	-0.021	-
			2	1	5.58	0.290	-0.084	-0.281	0.558
					7.23	-0.077	-0.306	0.230	0.595
2	1	16.69	0	1	1.42	-	-	0.234	-
					12.47	-	-	0.245	-
			1	1	9.55	-0.105	0.137	-0.028	-0.579
			2	1	5.58	0.277	0.089	0.314	0.323
					7.23	0.118	-0.046	-0.298	0.277
3	1	19.63	0	1	1.42	-	-	-	-0.276
					12.47	-	-	-	0.343
			1	1	9.55	-	-	0.340	0.008
			2	1	5.58	-0.252	-0.081	0.237	-0.373
					7.23	-0.442	-0.007	0.019	0.067

A = 13			B = 11			S_1	D_1	D_2	D_3
J	T	E_{calc}	J	T	E_{calc}				
1/2	1/2	0.00	1/2	1/2	1.71	0.112	0.308	-	-
					11.62	-0.521	0.179	-	-
			3/2	1/2	0.00	0.317	0.084	0.633	-
					5.39	-0.087	0.372	0.214	-
					11.44	-0.836	-0.017	-0.181	-
			5/2	1/2	4.35	-	-	0.241	0.462
					8.11	-	-	-0.209	1.064
			7/2	1/2	5.85	-	-	-	-1.336
1/2	1/2	8.78	1/2	1/2	1.71	0.510	0.272	-	-
					11.62	-0.080	-0.188	-	-
			3/2	1/2	0.00	-0.097	-0.647	0.157	-
					5.39	0.499	0.195	-0.301	-
					11.44	-0.217	0.403	0.153	-
			5/2	1/2	4.35	-	-	-0.437	0.314
					8.11	-	-	-0.590	-0.381
			7/2	1/2	5.85	-	-	-	0.195
3/2	1/2	3.59	1/2	1/2	1.71	0.332	-0.018	0.229	-
					11.62	-0.243	0.029	-0.318	-
			3/2	1/2	0.00	-0.033	0.180	-0.178	0.487
					5.39	-0.122	-0.310	0.398	0.013
					11.44	-0.014	-0.060	0.149	0.456
			5/2	1/2	4.35	0.308	-0.001	-0.206	0.386
					8.11	0.685	0.415	0.326	-0.302
			7/2	1/2	5.85	-	-	0.559	-0.419
			9/2	1/2	12.73	-	-	-	-0.213

A = 13			B = 11			S_1	D_1	D_2	D_3
J	T	E_{calc}	J	T	E_{calc}				
3/2	1/2	10.43	1/2	1/2	1.71	0.243	0.068	0.222	-
					11.62	0.157	0.122	-0.057	-
			3/2	1/2	0.00	-0.208	0.444	-0.136	0.012
					5.39	0.360	0.259	0.242	-0.123
					11.44	0.104	-0.205	-0.086	0.122
			5/2	1/2	4.35	0.399	0.318	0.032	0.083
					8.11	-0.054	-0.075	0.345	-0.444
			7/2	1/2	5.85	-	-	-0.600	0.132
			9/2	1/2	12.73	-	-	-	-0.720
5/2	1/2	7.40	1/2	1/2	1.71	-	-	-0.277	-0.023
					11.62	-	-	-0.312	-0.171
			3/2	1/2	0.00	-0.078	0.564	0.055	-0.012
					5.39	-0.024	0.019	0.143	0.193
					11.44	-0.020	-0.226	-0.279	-0.293
			5/2	1/2	4.35	-0.285	-0.273	-0.522	-0.198
					8.11	0.289	-0.039	0.182	0.014
			7/2	1/2	5.85	-0.534	-0.296	-0.282	0.116
			9/2	1/2	12.73	-	-	0.259	1.019
7/2	1/2	11.07	1/2	1/2	1.71	-	-	-	-0.229
					11.62	-	-	-	-0.092
			3/2	1/2	0.00	-	-	0.238	-0.011
					5.39	-	-	-0.026	0.240
					11.44	-	-	0.074	<0.001
			5/2	1/2	4.35	-0.190	0.195	-0.025	-0.314
					8.11	0.121	0.628	0.081	0.115
			7/2	1/2	5.85	-0.326	0.366	-0.128	0.032
			9/2	1/2	12.73	0.128	-0.084	-0.548	0.434
3/2	3/2	14.79	1/2	3/2	13.57	-0.369	-0.112	0.458	-
			3/2	3/2	15.85	0.553	0.073	0.244	0.654

A = 14			B = 12			S_1	D_1	D_2	D_3
J	T	E_{calc}	J	T	E_{calc}				
1	0	0.00	0	0	0.00	-0.101	0.492	-	-
					13.45	0.105	0.476	-	-
			2	0	4.65	-0.666	0.321	-0.572	-0.010
1	0	3.62	0	0	0.00	0.483	0.021	-	-
					13.45	0.336	0.085	-	-
			2	0	4.65	-0.030	-0.690	0.561	-0.587
2	0	6.99	0	0	0.00	-	-	0.257	-
					13.45	-	-	0.083	-
			2	0	4.65	-0.491	0.388	-0.143	-0.229
0	1	2.69	1	1	15.08	0.730	0.255	-	-
			2	1	16.69	-	-	1.077	-
			3	1	19.63	-	-	-	-1.955
1	1	11.78	0	1	19.59	-0.411	-0.120	-	-
			1	1	15.08	0.356	-0.234	-0.038	-
			2	1	16.69	0.248	-0.775	-0.168	0.109
			3	1	19.63	-	-	0.783	-0.220
2	1	9.52	0	1	19.59	-	-	0.400	-
			1	1	15.08	0.127	-0.583	-0.088	0.246
			2	1	16.69	0.053	-0.559	-0.021	-0.214
			3	1	19.63	0.584	0.199	0.261	-0.217

A = 16			B = 14			S_1	D_1	D_2	D_3
J	T	E_{calc}	J	T	E_{calc}				
0	0	0.00	1	0	0.00	0.103	-1.329	-	-
					3.62	-1.322	-0.231	-	-
			2	0	6.99	-	-	-1.807	-

A = 15			B = 13			S_1	D_1	D_2	D_3
J	T	E_{calc}	J	T	E_{calc}				
1/2	1/2	0.00	1/2	1/2	0.00	-0.248	0.764	-	-
					8.78	-0.543	-0.284	-	-
			3/2	1/2	3.59	0.863	0.293	0.631	-
					10.43	0.252	0.152	-0.779	-
			5/2	1/2	7.40	-	-	-0.928	0.250
			7/2	1/2	11.07	-	-	-	-1.541
3/2	1/2	6.36	1/2	1/2	0.00	-0.264	-0.091	0.233	-
					8.78	-0.026	-0.532	0.002	-
			3/2	1/2	3.59	0.413	-0.217	-0.026	0.376
					10.43	-0.057	-0.691	-0.092	-0.161
			5/2	1/2	7.40	-0.032	0.928	-0.314	0.084
			7/2	1/2	11.07	-	-	0.770	-0.465

TABLE II

Spectroscopic amplitudes for the transfer of two nucleons in the $(S, T = 0.1)$ state between normal parity states of 1p-shell nuclei. The states of the nucleus $A(B)$ are specified by the double spin and double isospin in the first row (first and second column) and the calculated excitation energy (in MeV) in the second row (third column), respectively. The orbitals of the transferred particle are in the third row

A = 7 / B = 5			1	1	3	1	3	1	5	1	5	1	7	1
			1.07		0.00		10.87		7.50		9.15		4.79	
			S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2
1	1	0.4	0.852	-	-	-0.513	-	0.104	-	-0.981	-	0.190	-	-
3	1	0.00	-	-0.854	-0.932	-0.568	-0.215	0.064	-	0.585	-	-0.409	-	1.174

A=8 / B=6			0	0	2	0	4	0	8	0	2	2	4	2	6	2
			0.00		14.98		3.41		11.29		16.88		15.80		17.49	
			S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2
2	0	0.00	-	-	-	-	-	-	-	-	0.102	0.234	-	-0.170	-	0.537
		5.05	-	-	-	-	-	-	-	-	-0.105	0.329	-	0.216	-	-0.168
4	0	5.23	-	-	-	-	-	-	-	-	-	0.188	-0.085	0.415	-	0.016
6	0	2.14	-	-	-	-	-	-	-	-	-	-0.580	-	0.750	-0.687	0.209
0	2	2.51	-1.230	-	-	-	-	-1.013	-	-	-	-	-	0.285	-	-
4	2	6.04	-	-1.055	-	-0.057	-1.015	-0.750	-	-1.602	-	-0.862	-0.429	0.062	-	-0.501

B=7 \ A=9			1 1 2.99		3 1 0.00		3 1 5.07		5 1 2.63		7 1 6.19		1 3 16.61		3 3 13.28	
			S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2
1	1	1.07	0.314	-	-	-0.266	-	0.620	-	-0.438	-	-	0.796	-	-	-0.369
3	1	0.00	-	-0.789	-0.326	0.737	0.060	0.374	-	0.448	-	0.537	-	-0.345	-0.818	0.153
		10.87	-	-0.067	-0.109	0.061	0.078	0.111	-	0.093	-	-0.151	-	0.324	-0.102	-0.062
5	1	7.40	-	-0.550	-	-0.321	-	-0.466	-0.158	0.180	-	-0.240	-	0.806	-	0.156
		9.15	-	-0.010	-	0.280	-	0.120	0.283	0.016	-	0.338	-	-0.227	-	-0.238
7	1	4.79	-	-	-	0.456	-	-0.488	-	-0.760	0.776	-0.127	-	-	-	-0.842

A=10 \ B=8			0 0 0.00		2 0 14.98		4 0 3.41		8 0 11.29		2 2 16.88		4 2 15.80		6 2 17.49	
			S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2
2	0	0.90	-	-	-	-	-	-	-	-	0.023	0.065	-	-0.460	-	-0.910
		2.38	-	-	-	-	-	-	-	-	-0.389	-0.932	-	0.669	-	-0.463
		6.19	-	-	-	-	-	-	-	-	-0.304	0.192	-	0.164	-	-0.113
4	0	3.34	-	-	-	-	-	-	-	-	-	-0.403	0.236	0.893	-	-0.193
		5.53	-	-	-	-	-	-	-	-	-	-0.178	-0.072	0.169	-	0.666
6	0	0.00	-	-	-	-	-	-	-	-	-	0.103	-	-0.769	0.743	-0.987
		4.72	-	-	-	-	-	-	-	-	-	0.196	-	0.534	-0.685	-0.652
0	2	1.42	-0.795	-	-	-	-	0.750	-	-	-	-	-	-0.710	-	-
		12.47	0.200	-	-	-	-	-0.146	-	-	-	-	-	-0.604	-	-
2	2	9.55	-	-	-0.028	0.325	-	0.071	-	-	0.395	-0.124	-	-0.482	-	-0.491
4	2	5.58	-	0.137	-	-0.128	0.615	-0.673	-	-0.494	-	0.334	0.478	0.325	-	0.555
		7.23	-	0.543	-	-0.029	-0.277	-0.656	-	0.667	-	-0.462	-0.244	0.133	-	0.075

A=11 \ B=9			1 1		3 1		3 1		5 1		7 1		1 3		3 3	
			2.99		0.00		5.07		2.63		6.19		16.61		13.28	
			S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2
1	1	1.71	0.800	-	-	-0.736	-	0.234	-	-0.257	-	-	-0.834	-	-	-0.969
		11.62	0.319	-	-	0.438	-	0.242	-	0.507	-	-	-0.096	-	-	-0.217
3	1	0.00	-	0.281	0.884	0.284	0.196	-0.265	-	-0.541	-	-0.700	-	0.156	-0.688	1.030
		5.39	-	0.139	0.155	0.368	-0.720	0.382	-	0.442	-	-0.682	-	0.948	-0.499	-0.389
		11.44	-	0.369	-0.038	0.255	0.126	-0.457	-	0.392	-	-0.004	-	-0.076	-0.011	-0.099
5	1	4.35	-	-0.066	-	0.074	-	0.050	0.738	-0.437	-	0.850	-	0.568	-	0.914
		8.11	-	0.266	-	-0.070	-	0.290	-0.053	0.209	-	0.261	-	-0.024	-	-0.225
7	1	5.85	-	-	-	0.705	-	0.114	-	-0.813	0.296	-0.906	-	-	-	0.067
9	1	12.73	-	-	-	-	-	-	-	0.279	-	0.425	-	-	-	-
1	3	13.57	-0.561	-	-	-0.900	-	-0.576	-	-0.547	-	-	-0.163	-	-	-0.466
3	3	15.83	-	0.278	-0.414	0.338	0.315	-0.497	-	0.817	-	-0.331	-	0.289	-0.033	0.022

A=12 / B=10			0 0 0.00		0 0 13.45		4 0 4.65		0 2 19.59		2 2 15.08		4 2 16.69		6 2 19.63	
			S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2
2	0	0.90	-	-	-	-	-	-	-	-	-0.239	-0.057	-	-0.081	-	-0.371
		2.38	-	-	-	-	-	-	-	-	0.029	0.151	-	-0.451	-	0.032
		6.19	-	-	-	-	-	-	-	-	-0.001	-0.190	-	-0.230	-	0.083
4	0	3.34	-	-	-	-	-	-	-	0.577	-	-0.093	-0.252	-0.032	-	-0.348
		5.53	-	-	-	-	-	-	-	0.814	-	0.020	-0.205	-0.213	-	0.158
6	0	0.00	-	-	-	-	-	-	-	-	-	0.987	-	-0.437	0.541	0.140
		4.72	-	-	-	-	-	-	-	-	-	0.102	-	0.236	-0.063	0.503
0	2	1.42	-1.365	-	-0.146	-	-	-0.545	0.144	-	-	-	-	-0.459	-	-
		12.47	0.001	-	0.813	-	-	0.039	0.742	-	-	-	-	-0.196	-	-
2	2	9.55	-	-	-	-	-	-0.091	-	-	-0.725	-0.069	-	0.117	-	-0.488
4	2	5.58	-	-0.885	-	0.452	0.966	-1.172	-	-0.079	-	0.280	-0.321	-0.737	-	-0.349
		7.23	-	1.720	-	0.840	0.550	0.927	-	-0.049	-	0.078	-0.516	0.232	-	0.071

B=11 \ A=13	1 1 0.00		1 1 8.78		3 1 3.59		3 1 10.43		5 1 7.40		7 1 11.07		3 3 14.79	
	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2	S_0	D_2
1 1 1.71	-0.446	-	0.121	-	-	0.425	-	-0.209	-	0.368	-	-	-	-0.318
11.62	-0.337	-	-0.350	-	-	0.132	-	-0.409	-	-0.240	-	-	-	0.268
3 1 0.00	-	-1.200	-	0.017	-0.334	0.211	0.261	0.070	-	0.135	-	0.267	0.667	0.174
5.39	-	0.159	-	-0.064	-0.250	0.516	-0.123	-0.219	-	-0.524	-	-0.031	0.096	-0.436
11.44	-	0.224	-	-0.150	0.441	-0.084	0.289	0.180	-	-0.137	-	0.396	-0.022	-0.170
5 1 4.35	-	-0.616	-	-0.065	-	0.835	-	-0.143	0.136	0.379	-	-0.409	-	-0.511
8.11	-	-0.154	-	-1.234	-	-0.016	-	0.718	-0.396	0.013	-	0.127	-	-0.088
7 1 5.85	-	-	-	-	-	-0.867	-	-0.401	-	-0.422	-0.672	-0.169	-	-1.078
9 1 12.73	-	-	-	-	-	-	-	-	-	-0.527	-	1.014	-	-
1 3 13.57	-1.170	-	-0.009	-	-	0.394	-	0.251	-	-0.667	-	-	-	-0.545
3 3 15.85	-	0.365	-	-0.511	-0.869	0.631	0.273	0.500	-	0.562	-	-0.556	-0.311	-0.535

A=14 / B=12	2 0 0.00		2 0 3.62		4 0 6.99		0 2 2.69		2 2 11.78		4 2 9.52	
	S_o	D_2	S_o	D_2	S_o	D_2	S_o	D_2	S_o	D_2	S_o	D_2
0 0 0.00	-	-	-	-	-	-	0.638	-	-	-	-	0.186
13.45	-	-	-	-	-	-	-0.077	-	-	-	-	0.137
4 0 4.65	-	-	-	-	-	-	-	-1.128	-	0.022	-0.499	-0.318
0 2 19.59	-	-	-	-	-	-0.635	-0.402	-	-	-	-	-0.044
2 2 15.08	-0.150	1.282	-0.376	0.024	-	-0.240	-	-	-0.694	-0.081	-	-0.169
4 2 16.69	-	-1.292	-	0.362	-0.531	0.197	-	-1.460	-	-0.188	0.631	-0.067
6 2 19.63	-	-0.011	-	-1.439	-	0.360	-	-	-	0.912	-	0.615

B=13 / A=15	1 1 0.00		1 1 8.78		3 1 3.59		3 1 10.43		5 1 7.40		7 1 11.07		3 3 14.79	
	S_o	D_2	S_o	D_2	S_o	D_2	S_o	D_2	S_o	D_2	S_o	D_2	S_o	D_2
1 1 0.00	-0.817	-	-0.014	-	-	0.796	-	0.363	-	1.567	-	-	-	**-1.578**
3 1 6.36	-	-0.245	-	-0.152	-0.680	-0.347	0.278	0.104	-	0.298	-	1.358	**-0.796**	**0.144**

B=14 / A=16	2 0 0.00		2 0 3.62		4 0 6.99		0 2 2.69		2 2 11.78		4 2 9.52	
	S_o	D_2	S_o	D_2	S_o	D_2	S_o	D_2	S_o	D_2	S_o	D_2
0 0 0.00	-	-	-	-	-	-	1.202	-	-	-	-	2.883

duct $[f_0]\times[2]$. The sum rule for stripping reads

$$\sum_{J_A T_A E_A LJ}\left(\frac{\hat{J}_A\hat{T}_A}{\hat{J}_B\hat{T}_B}S_{nLJ}\right)^2=\frac{A^2}{2(A-2)^2}\binom{A-4}{2}\sum_j c^2(j)\frac{\dim[f_{pj}]}{\dim(\lambda_j\mu_j)\dim[\tilde{f}_{pj}]}$$
$$\times\sum_{[f]}\frac{\dim(\lambda\mu)\dim[\tilde{f}]}{\dim[f]}, \tag{7}$$

where the subscript j refers to the states of a nucleus B. The summation runs only over those diagrams $[f]$ which appear in the product $[f_{pj}]\times[2]$. The dimensions of the representations $(\lambda\mu)$ and $[\tilde{f}]$ of the SU(3) and SU(4) group, respectively, are determined once $[f]$ is known.

The sum rules of Eqs (6) and (7) firstly enable one to check the calculations of the SAs. Similarly as in Refs [13, 15, 16] they can also be useful for predicting the selectivity of final states populated in one-step, direct 2N transfer reactions.

Considering a 2N transfer forming part of the multi-step sequential transfer of a few particles there are many excited, intermediate states from or to which 2N are transferred. Therefore the sum rules (6) and (7) cannot be immediately used in predicting the contribution of these states to 2N transfer. However, the contribution of the structural dependence[4] of these intermediate states can be deduced with the aid of the simple generalization (in the same way as in Refs [9, 10]) of the sum rule (6).

Eq. (6) is true for all states of the target nucleus A predicted by the model involved. Summing left and right-hand sides of (6) over all these states and taking into account the orthonormality condition of the coefficients $c(i)$ one finds that

$$\sum_{J_A T_A E_A J_B T_B E_B LJ}(S_{nLJ})^2=\frac{A^2}{2(A-2)^2}\binom{A-4}{2}\sum_i\frac{\mathcal{N}[f_{pi}]}{\dim[f_{pi}]}\sum_{[f_0]}\dim[f_0], \tag{8}$$

where $\mathcal{N}[f_{pi}]$ is the number of basis states (2) for the nucleus A specified by the Young diagram $[f_{pi}]$. By means of Eq. (8) one can calculate the quantity equal to $\sum_{J_A T_A E_A J_B T_B E_B LJ}(S_{nLJ})^2$. This quantity called the total strength [9, 10] can be a suitable means of predicting the contribution of the intermediate states to 2N transfer in one of a few steps of multi-step process[5]. In addition, the total strength defined by (8) can also be useful in discussing the selectivity of final states populated in 2N stripping and pickup (in contrast to the strength defined by (6) which may only be useful for pickup). The distribu-

[4] The contribution of any intermediate state to 2N transfer, similarly as in the case of any arbitrary particle transferred, depends on the dynamics of this process as well as on the structure of the states between which 2N are transferred. The SAs allow one to deduce structural dependence of this process only.

[5] Considering a transfer of 2N in the $(S, T = 1,0)$ state Eq. (8) includes only states of the nucleus B with $T_B = T_A$, in contrast to the case of 2N in the $(S, T = 0,1)$ state when summation on the left-hand side of (8) includes states of the nucleus B with $T_B = T_A-1$, T_A and T_A+1 for all states of the nucleus A.

tion of the total strength among intermediate states which can take part in 2N transfer process gives their structural selectivity in 2N transfer.

As an example of application of formula (8) the contribution of low-lying states to the deuteron transfer of an $(\alpha+d)$ process (i.e. a direct sequential transfer of the α-particle and d in the first and second step, respectively) of the $^{13}C/p$, $^{7}Be/^{7}Li^{*}$ reaction [4] is considered[6]. The allowed quantum numbers (J, T) of the intermediate states can be deduced from the angular momenta coupling rule and the law of parity conservation. However, one should remember that only those intermediate states most intensively populated by the α-particle transfer in the first step will essentially contribute to d transfer in the second step. The number of those predominant states can be selected by considering the distribution of the total strength among the intermediate states produced in the first step of the $(\alpha+d)$ process.

Fig. 1 illustrates the percentage distribution of the total strength among the most predominant intermediate states of the ^{9}Be nucleus (the $^{9}Be^{*} \rightarrow {}^{7}Li^{*}+d$ transition)

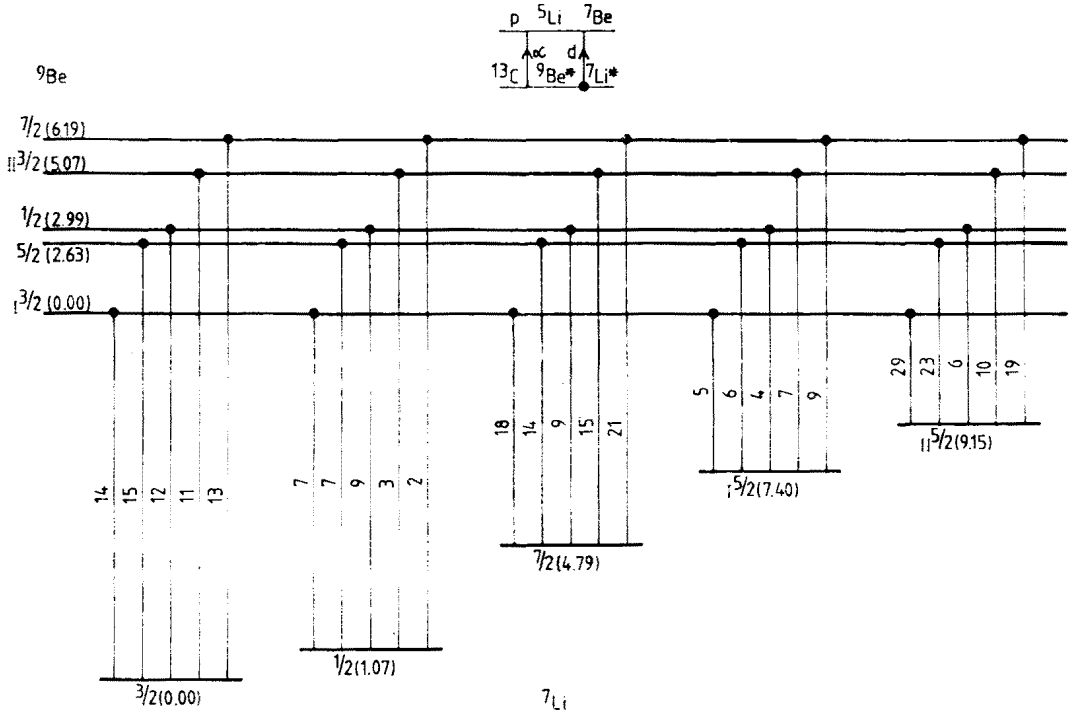

Fig. 1. The percentage distribution of the total strength among the intermediate states taking part in a deuteron transfer of the $(\alpha+d)$ process of the $^{13}C/p$, $^{7}Be/^{7}Li^{*}$ reaction for a few low-lying states of ^{7}Li in the exit channel (all numbers are multiplied by the factor 100). States of nuclei indicated are specified by the spin and calculated excitation energy (in brackets) in MeV

[6] The two-step $(\alpha+d)$ process seems to play important role in the mechanism of the $^{13}C/p$, $^{7}Be/^{7}Li^{*}$ reaction [4] because of the $\alpha+d$ cluster-like structure of the transferred ^{6}Li nucleus [22, 23].

for a few low-lying states of the ^{7}Li nucleus in the exit channel. The ratio of fractions of the total strength distributed among indicated intermediate states of ^{9}Be leading to the $J^\pi = 3/2^-, 1/2^-, 7/2^-, 5/2^-_I$ and $5/2^-_{II}$ states of ^{7}Li in exit channel is equal to 2.3:1:2.8:1.1:3.1, respectively. The contribution of any intermediate state to a deuteron transfer depends on the state of ^{7}Li in the exit channel. For example, in the case of the $5/2^-_{II}$ state of ^{7}Li the $3/2^-_I$, $5/2^-$ and $7/2^-$ intermediate states will participate in deuteron transfer at least twice more intensively than the $1/2^-$ and $3/2^-_{II}$ intermediate states.

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