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Low-energy neutron interaction with even-even nuclei and coupled channel optical model

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Abstract. We revised a description of low-energy neutron cross section data for even-even spherical nuclei in terms of the coupled channel optical model (CCOM). It is shown that two-phonon version of this model allows to obtain a unified description of these data assuming slight changes of nuclear diffuseness parameter for magic and near-magic nuclei. Neutron strength functions and scattering lengths for even-even spherical nuclei are also calculated using the same model. Results of these calculations are in a good agreement with experimental data. N_pN_n-systematics of inelastic neutron scattering on even-even nuclei is proposed. This systematics combined with CCOM calculations of neutron cross sections presents an additional method for finding nuclei with semimagic numbers of nucleons.

PACS. 24.10.Eq Coupled-channel and distorted wave models – 25.40.Fq Inelastic neutron scattering – 28.20.Cz Neutron scattering

1 Introduction

It is well-known that the low-energy neutron data for even-even nuclei are reasonably described in terms of the coupled channel optical model – CCOM (see e.g. [1]). However, an optimum description of neutron cross sections for isotopic chains (such as of Ge, Se, Cd, Sn, Te) [2–5] required individual values of the optical potential parameters for different isotopes, even in spite of taking into account the isospin dependence of the potential. Such differences can be rather significant, e.g. for ^{76}Se and ^{82}Se [2] the real potential depth values differ by $\approx 7\,$MeV. It should be noted that to obtain a satisfactory description of neutron data for the energies up to 3 MeV it is not sufficiant to use the simplest (one-phonon) version of CCOM as it was done in [1]. It is shown [4,6] that the two-phonon (five channel) version of CCOM is minimally necessary for such a description since it is more realistic than one-phonon (two-channel) approximation. But while the two-phonon version gives a description of the neutron data for Cd and Te isotope chains using practically the same CCOM parameter values [3,4] in the energy region under consideration, this version fails to give such a description of analogous data for the isotope chains of Ge, Se and Sn. There is no doubt that such a failure is connected with the fact that any optical model is unable to take into account effects of the nuclear shell structure which can lead to some "unregularities" in the A-dependence of the neutron cross sections. In other words, a unified description of low-energy neutron data for even-even nuclei seems to be imposible without taking into account shell effects. Emphasize that speaking about unified description of neutron data in the framework of CCOM we mean a description using the same set of the optical potetial parameter values for all the energy range and all the nuclei under consideration.

In Sect. 2 of this paper it is shown that a unified description of the neutron cross sections at energies up to 3 MeV for spherical even-even nuclei with $56 \leq A \leq 206$ may be obtained by use of slightly reduced values of the nuclear diffuseness parameter for magic and near-magic nuclei. Such a reduction effectively takes into account the influence of the nuclear shell structure on CCOM calculations. Note that the nuclear diffuseness reduction for magic and near-magic nuclei was proved theoretically and observed experimentally (see e.g. [7–9]).

Section 3 is devoted to calculations of the neutron strength functions and potential scattering lengths. Results of these calculations are compared with relevant experimental data.

In Sect. 4 we demonstrate that the inelastic neutron cross sections corresponding to the excitation of 2_1^+ levels show a smooth dependence on the product N_pN_n of the valence proton and neutron numbers (so-called N_pN_n-systematics). This systematics together with similar N_pN_n-dependences of some spectroscopic data (see e.g. [10]) can help in finding "non-traditional" magic or semimagic numbers of protons and neutrons.

Section 5 presents the conclusion of the paper.

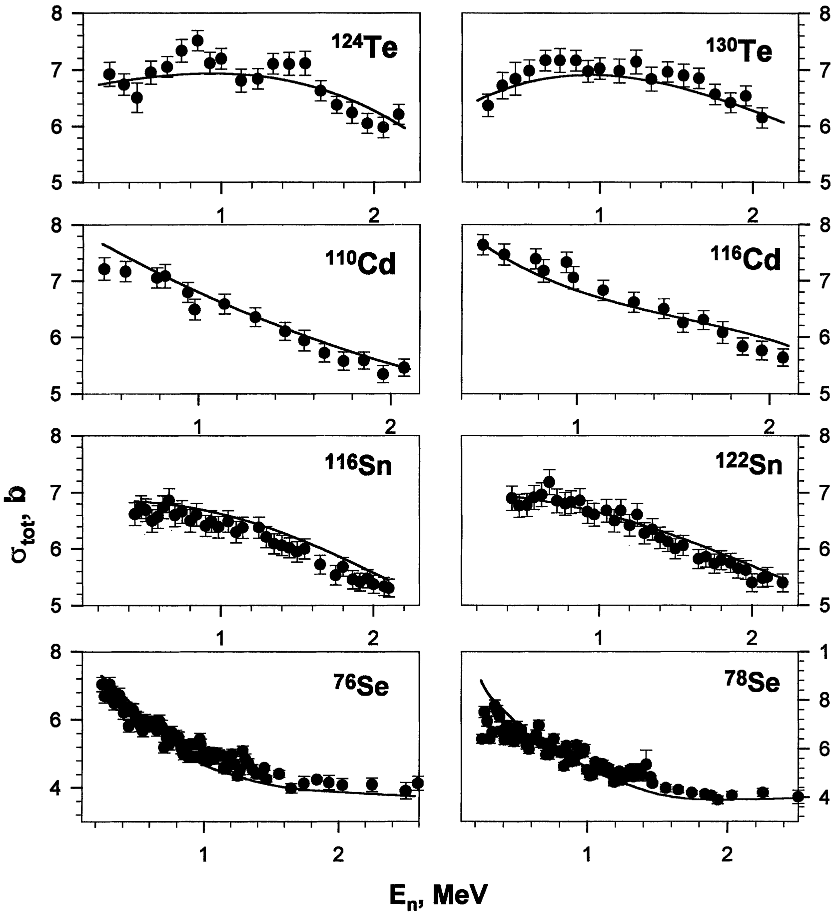

Fig. 1. Neutron total cross sections for ^{76,78}Se, ^{110,116}Cd, ^{116,122}Sn, and ^{124,130}Te. Experimental points are taken from [2,4,35]. Solid curves present CCOM calculation results of this paper

2 Description of neutron cross sections

To obtain an optimum description of neutron cross sections we reconsidered the experimental data on total, inelastic and differential elastic and inelastic cross sections for $0.07\,\mathrm{MeV} \leq E_n \leq 3.00\,\mathrm{MeV}$ for even-even spherical nuclei with $56 \leq A \leq 206$ in terms of the two-phonon version of CCOM. For our analysis we used experimental data obtained at the Institute for Nuclear Research of Russiam Academy of Sciences (see refs. cited above) together with results of other laboratories (e.g. [11,12]). To describe A- and E-dependences of the average neutron cross sections we used the formalism propose by Hofmann, Rihert, Tepel and Weidenmüller [13]. The method of calculation is described in details in [14].

For our calculation we used nonspherical optical potential with the real part of Woods-Saxon's form. The real part included the spin-orbital term and the symmetry potential. Radial dependence of the imaginary part was taken as the derivative of the real part. Geometrical parameters of the potential were the same for real and imaginary parts: the potential radius was fixed as $R = r_0 A^{1/3}$ with $r_0 = 1.22\,\mathrm{fm}$; the nuclear diffuseness parameter a was initially taken to be equal to 0.65 fm, but as it was pointed out in the Introduction it was slightly changed for some nuclei in order to obtain better description. The spin-orbit interaction parameter V_{so} was equal to 8 MeV. The depth of the real potential together with the isospin-dependent term was chosen as $V = V_0 - V_1(N-Z)/A$ with $V_1 = 22\,\mathrm{MeV}$. The depths of real and imaginary parts V_0 and W were two free parameters to fit. As to the diffuseness a it was a kind of a "half-free" parameter since it was slightly changed (starting from the initial value of 0.65 fm) only for several nuclei. The values of the quadrupole deformation parameter β_2, which define matrix elements of channel coupling, were taken from [15], though generally speaking, the deformation parameters could be regarded as phenomenological ones.

The model parameters were determined for each nucleus proceeding from the requirement of an optimum description of the energy dependences for the total and inelastic cross sections, differential cross sections of elastic and inelastic scattering for the energy range under consideration. As a criterion of an optimum description the value of χ^2 was taken.

Figures 1–4 demonstrate typical examples of our description of the experimental data. One can see a good agreement between the calculated curves and experimental points. Note that almost in all the cases of the energy and angular dependences we obtained $\chi^2 \leq 1.0$. Only for a few nuclei having considerable fluctuations in the energy dependences of cross sections the description of those de-

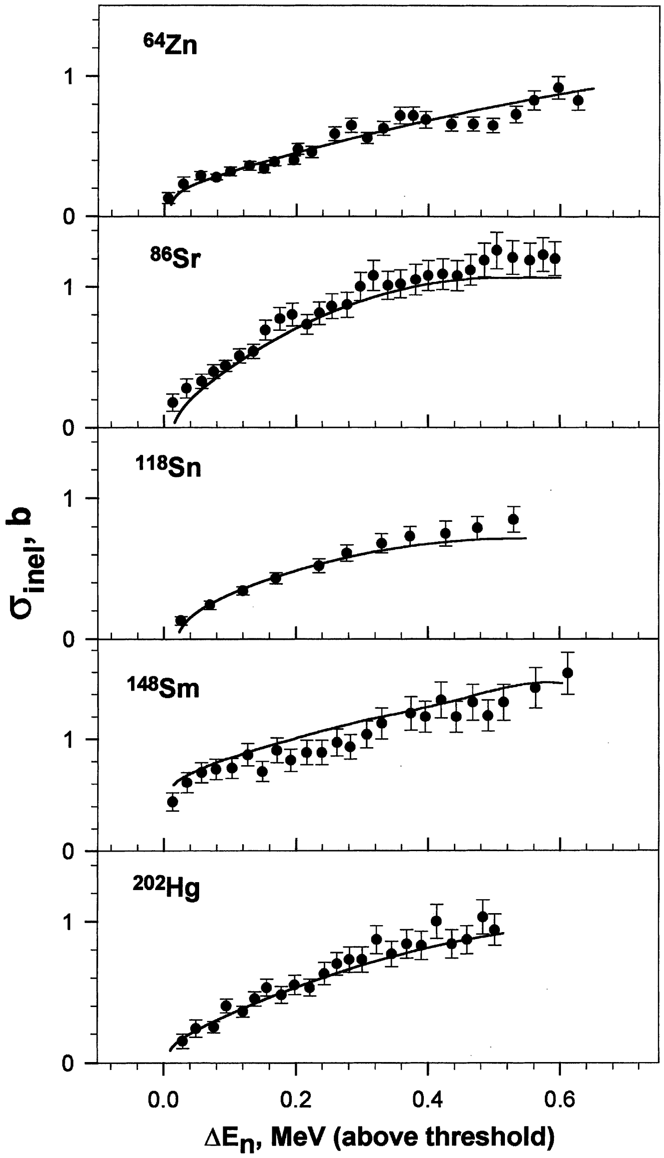

Fig. 2. Neutron inelastic cross sections for ^{64}Zn, ^{86}Sr, ^{118}Sn, ^{148}Sm, and ^{202}Hg. Experimental points are taken from [1]. Solid curves – CCOM calculation of this paper

pendences was somewhat worse, but anyway the χ^2 value never exceeded 2.0.

Table 1 presents the model parameter values obtained in our analysis for each nucleus. The Table also contains experimental values of the inelastic cross sections with excitation of the 2_1^+ levels taken at the energy 300 keV above threshold and averaged over 100 keV, calculated values of these cross sections, χ^2 values characterizing quality of the inelastic cross section description, and the valence nucleon product values (N_pN_n). We need all that for considering the N_pN_n systematics of neutron inelastic scattering (see below).

As it was noted above, in some cases we altered the diffuseness parameter values (as compared to initial $a = 0.65$ fm) to obtain better description ($\chi^2 \leq 1$). Such alteration was done for magic and near-magic nuclei since there are experimental and theoretical indications [7–9] about some reduction of the surface layer (i.e. diffuseness) for nuclei with closed shells. An example of such a reduction gives the chain of Sn isotopes ($Z = 50$): a good description of the total cross sections for $^{112-124}$Sn was achieved at $a = 0.60$ fm ($V_0 = 53.5 \pm 1.0$ MeV and $W = 2.5 \pm 0.5$ MeV) except for ^{114}Sn (see below). This reduction of a allowed to improve quality of the cross section description considerably: at $a = 0.60$ fm we obtained $\chi^2 \leq 1$ instead of $\chi^2 = 2 - 6$ for different isotopes at $a = 0.65$ fm. As a rule the a value for magic (and sometimes for near-magic) nuclei was equal to 0.60 fm; the minimal a value was equal to 0.57 fm for ^{140}Ce ($N = 82$). Note that for ^{206}Pb ($Z = 82$) the a value obtained in our analysis was also reduced, but the analysis was made difficult for this isotope because of considerable fluctuations in the inelastic cross section.

Emphasize that using reduced a values for magic and near-magic nuclei allowed not only to improve description of neutron data for these nuclei, but also to describe low-energy neutron data for a large number of even-even spherical nuclei in terms of the two-phonon version of CCOM, using practically the same values of model parameters V_0 and W, namely $V_0 = 52.5 \pm 1.5$ MeV and $W = 2.5 \pm 0.5$ MeV.

The unified description seems to be broken only for nuclei which can be considered as having so-called "semimagic" numbers [10] of nucleons: neutron cross sections for such nuclei, as a rule, differ significantly from coresponding cross sections for neighbouring even-even nuclei. The most clear examples of such a behaviour present even-even isotopes of Ge and Se, neutron cross sections of which having strong dependence on the number of neutrons. For instance, experimental values of the inelastic scattering cross section with 2_1^+ level excitation for neighbouring isotopes ^{70}Ge and ^{72}Ge differ by factor ≈ 1.7 (see Table 1). Such a difference may be explained by appearance (and disappearance) of a new energy gap when neutron subshell $f_{5/2}$ is closed. If it is so the neutron number $N = 38$ can be regarded as a semimagic number (less steady than the traditional magic numbers of nucleons).

The problem of the semimagic number existence is often correlated with the question on the nuclear diffuseness value in CCOM. This correlation can be demonstrated in the case of Ge and Se isotopes for which the surface layer thickness (diffuseness) is known from the analysis of the elastic electron scattering data at 225 MeV [9]. In the chain of Ge isotopes the diffuseness is minimal for ^{70}Ge, for ^{72}Ge it increases, becomes maximal for ^{74}Ge and starts decreasing for ^{76}Ge. Note that to obtain a better description of neutron data for Ge and Se isotopes we had to use the parameter a values which were bigger than the initial 0.65 fm (see Table 1), namely the values given by experiments [9].

Another example of the correlation between diffuseness and semimagic numbers presents ^{114}Sn. This nucleus may be considered as twice magic [6] because its neutrons ($N = 64$) seem to form the closed shell ($1g_{7/2}$ and $2d_{5/2}$). As a consequence, the parameter a value taken for the optimum

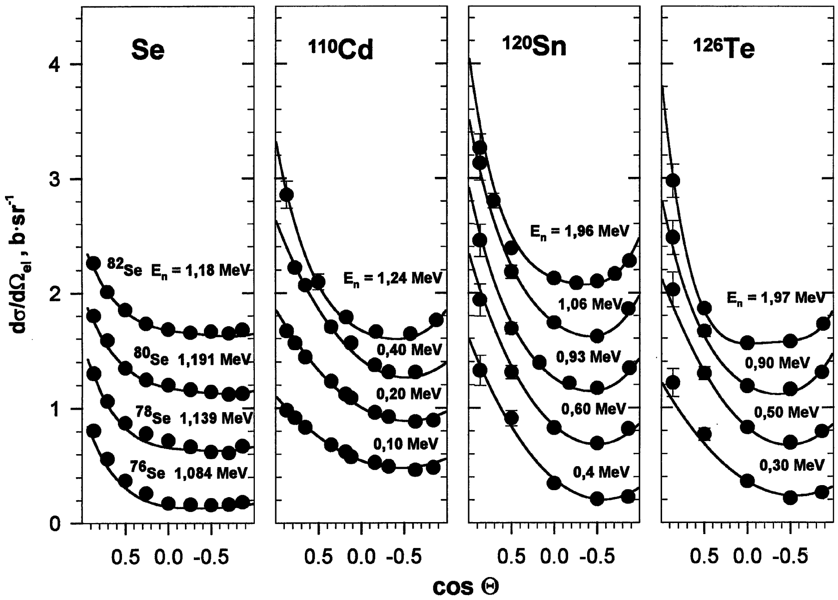

Fig. 3. Differential cross sections of low-energy neutron elastic scattering on $^{76-82}$Se, ^{110}Cd, ^{120}Sn, and ^{126}Te. Experimental points are taken from [2,4,35]. Solid curves – CCOM calculation results of this paper. The curves of each plot are shifted up (together with corresponding experimental points) by 0.5 b one from the other

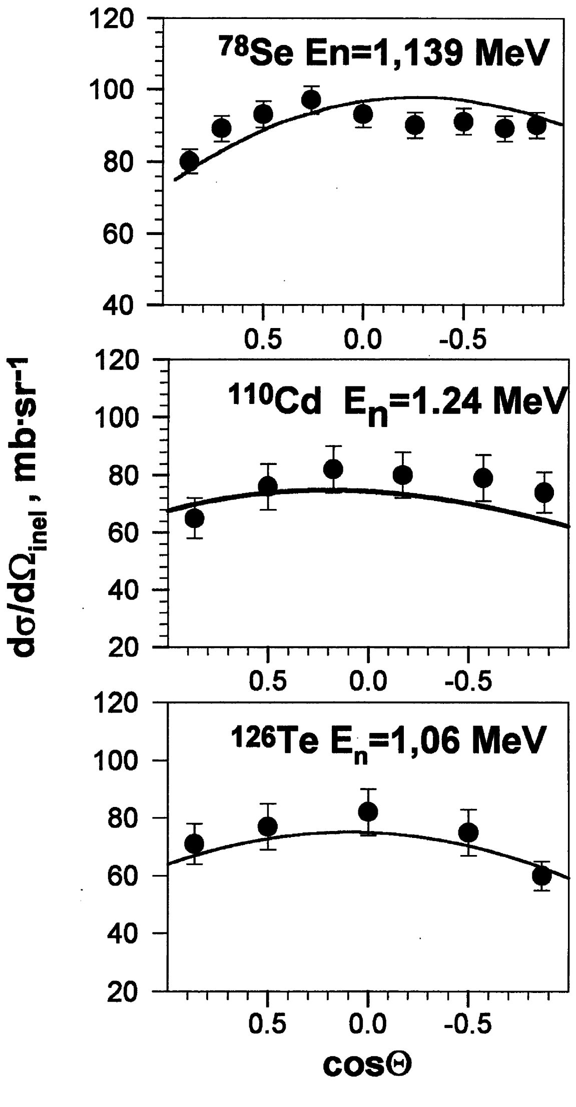

Fig. 4. Differential cross sections of low-energy neutron inelastic scattering on ^{78}Se, ^{110}Cd, and ^{126}Te. Experimental points are taken from [2,4,35]. Solid curves – CCOM calculation results of this paper

description of total cross sections (the only neutron data available for this nucleus) was equal to 0.5 fm.

Thus, the results reported above show a possibility to describe the totality of existing data on low-energy neutron cross sections for even-even spherical nuclei in terms of the two-phonon version of CCOM using one set of the model parameters. And that stimulated us to consider neutron strength functions and potential scattering lengths for such nuclei in the same model approach.

3 Neutron strength functions and potential scattering lengths

Neutron strength functions S_l ($l = 0, 1, 2$) are defined from the experimental data as $S_l = \langle \Gamma_n^{(l)} \rangle / \langle D^{(l)} \rangle$, where $\langle \Gamma_n^{(l)} \rangle$ is the average reduced width of a compound nucleus for neutron angular momentum l, $\langle D^{(l)} \rangle$ is the average distance between corresponding energy levels.

At present the S_0 values are known for the majority of stable nuclei [16–18], and a considerable part of this information is obtained from the analysis of isolated resonances. Experimental data on S_1 are not so numerous, they are obtained mainly for nuclei with $A \simeq 100$ and for some of the rare earth nuclei. Note that in many cases the S_1 values obtained by different methods differ significantly. In this connection we mention a method proposed by G.S. Samosvat [19,20] and based on a spectroscopic analysis of the differential cross sections of low-energy neutron elastic scattering. This method seems to be more reliable in obtaining the S_1 values together with potential

Table 1. Parameters of even-even spherical nuclei. The N_pN_n values marked by * are obtained assuming the existence of semimagic numbers $Z = N = 40$ (^{76}Se, ^{98,100}Mo), $Z = 56$ (^{142}Ce), $N = 64$ ($^{108-116}$Cd)

Nucleus	Z	N	N_pN_n	σ_{inel}^{exp}, b	σ_{inel}^{theor}, b	χ^2	V_0, MeV	W, MeV	a, fm
^{60}Ni	28	32	0	0.60(9)	0.52	1.29	51.0	3.0	0.65
^{64}Zn	30	34	8	0.63(5)	0.61	1.02	53.5	2.5	0.65
^{66}Zn	30	36	4	0.59(6)	0.55	1.42	53.0	3.0	0.65
^{68}Zn	30	38	0	0.50(5)	0.49	1.06	52.0	2.0	0.65
^{70}Ge	32	38	0	0.65(7)	0.68	0.98	53.0	3.0	0.65
^{72}Ge	32	40	40	1.12(12)	1.07	0.33	53.0	2.0	0.75
^{74}Ge	32	42	32	1.28(16)	1.26	0.91	52.0	2.0	0.80
^{76}Ge	32	44	24	1.15(14)	1.23	1.10	52.0	2.0	0.75
^{76}Se	34	42	12*	0.94(13)	0.96	0.62	52.0	2.0	0.70
^{78}Se	34	44	36	1.23(15)	1.13	0.63	52.0	2.0	0.75
^{80}Se	34	46	24	0.95(12)	0.95	0.23	53.0	2.0	0.65
^{86}Sr	38	48	20	0.95(10)	0.90	0.98	53.5	2.0	0.65
^{92}Zr	40	52	20	1.06(12)	0.95	1.12	53.0	2.0	0.65
^{94}Zr	40	54	40	1.12(13)	1.00	0.97	52.5	2.0	0.65
^{94}Mo	42	52	16	1.08(12)	1.00	0.70	51.5	2.0	0.65
^{96}Mo	42	54	32	1.05(10)	1.02	0.82	51.0	2.0	0.65
^{98}Mo	42	56	12*	0.82(8)	0.87	0.94	51.5	2.0	0.65
^{100}Mo	42	58	16*	1.00(15)	0.93	0.70	50.5	2.0	0.65
^{108}Cd	48	60	8*	0.81(17)	0.67	0.95	52.0	3.0	0.60
^{110}Cd	48	62	4*	0.75(10)	0.66	0.99	52.5	3.0	0.60
^{112}Cd	48	64	0*	0.80(12)	0.70	0.87	54.0	3.0	0.60
^{114}Cd	48	66	4*	0.74(11)	0.67	0.60	52.5	3.0	0.60
^{116}Cd	48	68	8*	0.69(13)	0.69	1.16	52.5	2.5	0.60
^{116}Sn	50	66	0	0.65(13)	0.62	0.92	52.5	2.5	0.60
^{118}Sn	50	68	0	0.63(6)	0.63	0.38	52.5	2.5	0.60
^{120}Sn	50	70	0	0.55(5)	0.59	0.65	52.0	2.0	0.60
^{122}Sn	50	72	0	0.53(6)	0.54	0.52	52.0	2.0	0.60
^{124}Sn	50	74	0	0.49(6)	0.50	0.41	53.0	2.0	0.60
^{122}Te	52	70	24	0.87(9)	0.86	1.14	52.0	3.0	0.65
^{124}Te	52	72	20	0.90(9)	0.91	1.22	53.0	3.0	0.65
^{126}Te	52	74	16	0.80(8)	0.84	0.65	52.0	3.0	0.65
^{128}Te	52	76	12	0.69(7)	0.73	0.35	52.0	2.0	0.65
^{136}Ba	56	80	12	0.66(10)	0.57	0.88	52.0	2.0	0.60
^{138}Ba	56	82	0	0.48(6)	0.44	1.11	53.0	2.0	0.60
^{140}Ce	58	82	0	0.62(6)	0.67	0.55	52.0	2.0	0.57
^{142}Ce	58	84	4*	0.60(8)	0.63	0.74	51.0	2.0	0.60
^{148}Sm	62	86	48	1.03(13)	1.07	0.90	53.0	2.5	0.65
^{192}Os	76	116	60	1.38(16)	1.35	0.23	53.0	2.0	0.65
^{198}Pt	78	120	24	1.29(20)	1.13	0.90	51.0	2.5	0.65
^{198}Hg	80	118	16	0.93(12)	0.94	0.33	53.5	3.0	0.60
^{200}Hg	80	120	12	0.88(9)	0.80	1.20	53.0	3.0	0.60
^{202}Hg	80	122	8	0.78(8)	0.72	0.80	53.5	2.0	0.60
^{204}Hg	80	124	4	0.75(13)	0.73	0.60	52.5	2.5	0.60
^{206}Pb	82	124	0	0.48(5)	0.44	2.09	53.0	2.0	0.60

scattering lengths R'_0 and R'_1 for even-even nuclei. As to the data on S_2 they are rather scarce now since the d-neutrons resonances are not studied sufficiently well.

In spite of existing many phenomenological and microscopic approaches to the theoretical description of neutron strength functions and potential scattering lengths there is no approach which would give a satisfactory description of them together with other low-energy neutron data. The main trouble is a poor description of the positions and the magnitudes of deep minima observed for S_0 (at $A \simeq 120$) and for S_1 (at $A \simeq 54$) as it was pointed out earlier [16].

We have calculated S_0, S_1, S_2, R'_0 and R'_1 for 56 even-even spherical nuclei with $58 \leq A \leq 206$ using two-phonon version of CCOM with the model parameter values defined for the optimum description of low-energy neutron cross sections (see previous section). Our results are presented in Tables 2 and 3 together with the experimental values of S_0, S_1, S_2, R'_0 and R'_1 taken from the compilations

Table 2. Strength functions and potential scattering lengths for *s*- and *p*-wave neutrons

	$S_0 \times 10^4$		$S_1 \times 10^4$		R'_0, fm		R'_1, fm	
Nucleus	exp.	theor.	exp.	theor.	exp.	theor.	exp.	theor.
^{58}Ni	2.8 ± 0.6[16]	3.1	0.5 ± 0.1[16]	0.33	8.0 ± 0.5[16]	7.0		3.0
	3.26 ± 0.59[18]							
^{60}Ni	2.7 ± 0.6[16]	3.2	0.3 ± 0.1[16]	0.35	6.7 ± 0.3[16]	6.6		2.8
	3.05 ± 0.57[18]							
^{62}Ni	2.8 ± 0.7[16]	3.5	0.3 ± 0.1[16]	0.36	6.2 ± 0.3[16]	6.3		2.5
	2.70 ± 0.60[18]							
^{64}Ni	2.9 ± 0.8[16]	3.2	0.6 ± 0.2[16]	0.50	7.6 ± 0.3[16]	6.9		3.0
	2.10 ± 0.40[18]							
^{64}Zn	1.70 ± 0.16[16]	2.4	0.60 ± 0.04[16]	0.70		7.3		0.93
	1.89 ± 0.26[18]							
^{66}Zn	1.9 ± 0.2[16]	2.5	0.70 ± 0.07[16]	0.70		7.3		0.52
	2.06 ± 0.36[18]							
^{68}Zn	2.2 ± 0.3[16]	2.5	0.39 ± 0.03[16]	0.51		7.3		0.80
	2.01 ± 0.34[18]							
^{70}Zn	1.8 ± 0.3[16]	2.2	1.45 ± 0.40[16]	0.90		7.1		11.6
	2.05 ± 0.35[18]							
^{70}Ge	2.1 ± 0.9[16]	2.1		1.0	6.9 ± 0.1[16]	6.9		1.5
	1.90 ± 0.30[18]							
^{72}Ge	1.66 ± 0.50[16]	1.5		2.0	6.9 ± 0.1	7.0		1.9
	1.50 ± 0.40[18]							
^{74}Ge	1.5 ± 0.7[16]	1.8		2.0	6.9 ± 0.1[16]	6.9		0.64
	2.3 ± 0.8[18]							
^{76}Ge	1.78 ± 0.02[16]	1.7		3.2		7.0		3.1
	1.60 ± 0.50[18]							
^{74}Se	1.29 ± 0.80[16]	1.3		3.4	7.5 ± 0.7[16]	6.9		3.0
	3.10 ± 0.70[18]							
^{76}Se	1.64 ± 0.60[16]	1.6	0.94 ± 0.60[16]	0.93	7.5 ± 0.7[16]	7.4		1.3
	2.40 ± 0.50[18]							
^{78}Se	1.23 ± 0.60[16]	1.5	1.7 ± 1.0[16]	3.6	8.3 ± 0.8[16]	6.7		2.0
	1.50 ± 0.60[18]							
^{80}Se	1.6 ± 1.0[16]	1.6	0.5 ± 0.5[16]	0.97	8.7 ± 0.8[16]	7.1		1.2
	2.7 ± 1.2[18]							
^{82}Se	1.2 ± 1.0[16]	1.4		1.9	7.5[16]	7.1		1.6
	3.10 ± 0.70[18]							
^{84}Sr	0.87 ± 0.39[16]	0.76		1.6		6.9		4.3
	0.80 ± 0.30[18]							
^{86}Sr	0.62 ± 0.10[16]	0.64		1.6		6.9		4.2
	0.70 ± 0.20[18]							
^{88}Sr	0.45 ± 0.10[16]	0.65	4.98 ± 0.74[16]	4.2	7.1 ± 0.1[16]	6.6		4.1
	0.41 ± 0.12[18]							
^{90}Zr	0.7 ± 0.2[16]	0.53	4.0 ± 0.6[16]	4.0	7.2 ± 0.2[16]	6.7		4.6
	0.54 ± 0.10[18]							
^{92}Zr	0.50 ± 0.10[16]	0.61	7.0 ± 1.3[16]	6.0	7.2 ± 0.2[16]	6.7		7.0
	0.70 ± 0.15[18]							
^{94}Zr	0.50 ± 0.15[16]	0.40	9.8 ± 2.0[16]	6.0	7.2 ± 0.2[16]	6.6		7.5
	0.72 ± 0.16[18]							
^{96}Zr	0.34 ± 0.14[16]	0.39	6.0 ± 1.8[16]	5.5	7.2 ± 0.2[16]	6.7		7.8
	0.30 ± 0.15[18]							
^{92}Mo	0.50 ± 0.20[16]	0.65	4.7 ± 1.5[16]	4.2	7.0 ± 0.2[16]	6.5	2.25 ± 0.91[21]	2.8
	0.56 ± 0.07[18]		3.39 ± 0.87[21]					
			2.4 ± 0.9[22]					
^{94}Mo	0.53 ± 0.20[16]	0.58	4.6 ± 2.0[16]	5.9	7.2 ± 0.2[16]	6.6	3.18 ± 0.60[21]	2.9
	0.44 ± 0.08[18]		4.25 ± 0.66[21]					
			4.2 ± 1.0[22]					
^{96}Mo	0.43 ± 0.14[16]	0.61	8.7 ± 2.8[16]	5.0	7.0 ± 0.2[16]	6.5		3.1
	0.62 ± 0.12[18]		4.5 ± 1.0[22]					

Table 2. Continued.

	$S_0 \times 10^4$		$S_1 \times 10^4$		R'_0, fm		R'_1, fm	
Nucleus	exp.	theor.	exp.	theor.	exp.	theor.	exp.	theor.
^{98}Mo	0.54 ± 0.12[16]	0.57	3.6 ± 0.6[16]	5.0	6.9 ± 0.2[16]	6.5		3.3
	0.48 ± 0.09[18]		8.0 ± 1.5[22]					
^{100}Mo	0.73 ± 0.17[16]	1.0	4.4 ± 0.9[16]	4.0	6.9 ± 0.2[16]	6.2		0.64
	0.65 ± 0.10[18]		5.5 ± 0.7[22]					
	0.51 ± 0.18[22]							
^{106}Cd	1.00 ± 0.35[16]	0.71	5.0 ± 1.5[16]	5.0		5.8	8.7 ± 0.6[21]	8.1
	1.00 ± 0.35[18]		4.11 ± 0.64[21]					
^{108}Cd	1.2 ± 0.4[16]	0.6	4.8 ± 1.3[16]	5.2		5.8	9.9 ± 0.8[21]	8.9
	1.16 ± 0.46[18]		4.40 ± 0.54[21]					
^{110}Cd	0.44 ± 0.11[16]	0.5	3.0 ± 1.0[16]	5.3	6.6 ± 0.1[22]	5.8	10.7 ± 0.8[21]	9.9
	0.28 ± 0.07[18]		5.40 ± 0.43[21]					
			2.6 ± 0.5[22]					
^{112}Cd	0.5 ± 0.1[16]	0.5	4.4 ± 1.0[16]	5.0	6.5 ± 0.1[22]	5.8	10.4 ± 0.6[21]	10.1
	0.5 ± 0.1[18]		4.39 ± 0.36[21]					
			3.5 ± 0.7[22]					
^{114}Cd	0.64 ± 0.16[16]	0.6	3.5 ± 1.0[16]	4.9	6.5 ± 0.1[22]	5.8		10.1
	0.64 ± 0.16[18]		4.2 ± 0.3[21]					
			5.6 ± 0.6[22]					
^{116}Cd	0.16 ± 0.05[16]	0.6	2.8 ± 0.8[16]	4.9		5.7	10.5 ± 0.6[21]	10.0
	0.16 ± 0.05[18]		3.99 ± 0.50[21]					
^{112}Sn	0.3 ± 0.1[16]	0.34	3.5 ± 0.4[23]	5.7	5.8 ± 0.2[23]	6.0	8.2 ± 0.3[23]	9.9
	0.3 ± 0.1[18]			2.9				
^{114}Sn	0.2 ± 0.1[16]	0.25	2.8 ± 0.3[23]	4.7	6.3 ± 0.3[16]	5.9	7.8 ± 0.3[23]	8.6
	0.2 ± 0.1[18]			2.4	5.9 ± 0.2[23]			
^{116}Sn	0.40 ± 0.25[18]	0.27	3.81 ± 0.35[21]	4.2	6.2 ± 0.1[16]	5.9	11.3 ± 0.4[21]	11.2
	0.18 ± 0.04[22]		2.7 ± 0.7[22]	2.3	5.8 ± 0.2[23]		8.2 ± 0.3[23]	
	0.26 ± 0.05[30]		2.3 ± 0.2[23]					
^{118}Sn	0.46 ± 0.21[18]	0.27	2.91 ± 0.42[21]	4.2	6.0 ± 0.2[16]	5.9	11.8 ± 0.6[21]	11.1
	0.09 ± 0.02[22]		2.7 ± 0.7[22]	2.0	6.1 ± 0.2[22]		8.5 ± 0.3[23]	
	0.16[23]		2.1 ± 0.2[23]		5.6 ± 0.2[23]			
^{120}Sn	0.14 ± 0.02[16]	0.28	2.1 ± 0.2[16]	4.0	6.1 ± 0.1[22]	5.8	11.1 ± 0.3[21]	10.9
	0.14 ± 0.03[18]		2.15 ± 0.23[21]	2.0	6.1 ± 0.2[23]		8.7 ± 0.3[23]	
	0.06 ± 0.04[22]		2.0 ± 0.6[22]					
			1.6 ± 0.2[23]					
^{122}Sn	0.17 ± 0.05[16]	0.29	3.08 ± 0.42[21]	3.7	5.7 ± 0.3[16]	5.7	12.5 ± 0.6[21]	12.4
	0.123 ± 0.023[24]		2.7 ± 0.7[22]	1.8	6.1 ± 0.1[22]		8.6 ± 0.3[23]	
			1.4 ± 0.2[23]		6.1 ± 0.2[23]			
			2.0 ± 0.2[24]		6.3 ± 0.1[24]			
^{124}Sn	0.15 ± 0.08[16]	0.24	3.53 ± 0.35[21]	3.5	5.9 ± 0.2[16]	5.8	12.2 ± 0.6[21]	11.5
	0.12 ± 0.03[18]		3.0 ± 0.8[22]	1.7	6.0 ± 0.1[22]		8.7 ± 0.3[23]	
	0.19 ± 0.03[22]		1.4 ± 0.2[23]		6.1 ± 0.2[23]		10.5 ± 0.3[24]	
	0.12 ± 0.03[24]		1.8 ± 0.2[24]		6.4 ± 0.2[24]			
^{122}Te	0.83 ± 0.20[16]	0.73		4.0	5.9 ± 0.2[16]	5.7		9.4
	0.83 ± 0.12[18]							
^{124}Te	0.60 ± 0.12[16]	0.73		4.0	5.9 ± 0.2[16]	5.7		9.4
	0.83 ± 0.12[18]							
^{126}Te	0.28 ± 0.10[16]	0.37		4.1	5.6 ± 0.2[16]	5.6		11.9
^{128}Te	0.25 ± 0.10[16]	0.35		4.4	5.5 ± 0.3[16]	5.6		12.4
^{130}Te	0.16 ± 0.05[16]	0.25		3.7	5.4 ± 0.3[16]	5.8		10.5
^{134}Ba	0.53 ± 0.14[16]	1.05	0.8 ± 0.3[16]	1.9		4.7		11.4
	1.40 ± 0.40[18]		3.2 ± 0.6[31]					
^{136}Ba	0.8 ± 0.3[16]	0.69	1.8 ± 0.3[31]	2.0	5.45[22]	5.1		10.5
	0.86 ± 0.23[18]		1.15 ± 0.28[32]					
	0.9 ± 0.3[22]							
^{138}Ba	1.6 ± 0.4[16]	0.64	0.98 ± 0.28[32]	1.5	5.45[22]	5.1		11.0
	0.66 ± 0.28[18]							

Table 2. Continued.

Nucleus	$S_0 \times 10^4$ exp.	$S_0 \times 10^4$ theor.	$S_1 \times 10^4$ exp.	$S_1 \times 10^4$ theor.	R'_0, fm exp.	R'_0, fm theor.	R'_1, fm exp.	R'_1, fm theor.
^{140}Ce	1.1 ± 0.3[16] 1.20 ± 0.30[18]	0.83	0.34 ± 0.05[27]	0.90	5.7 ± 0.5[16] 5.1 ± 0.3[27]	5.2		9.7
^{142}Ce	1.2 ± 0.5[16]	0.73		1.7	5.9 ± 0.7[16]	5.1		11.2
^{144}Nd	4.0 ± 1.0[16] 5.1 ± 0.9[18]	4.4	0.5 ± 0.2[16]	1.0	6.0 ± 0.5[16]	3.7		8.4
^{144}Sm	3.2 ± 1.4[17] 3.6 ± 0.8[18]	4.0		0.80		3.0		8.5
^{148}Sm	3.80 ± 0.80[18]	3.8	1.91 ± 0.46[29]	1.3	5.1 ± 0.3[27]	5.0		9.0
^{192}Os	2.4 ± 0.5[28]	3.0	$0.73^{+0.51}_{-0.39}$[26]	0.50		8.0		4.0
^{198}Pt	1.4 ± 0.6[18] 1.3 ± 0.5[26]	2.0		0.58	9.4 ± 0.2[17]	9.3		5.0
^{202}Hg	1.4 ± 0.5[28]	2.0	$0.06^{+0.04}_{-0.03}$[28] 0.25[28]	0.4		9.5		4.0
^{204}Pb	0.65 ± 0.12[17] 1.10 ± 0.20[18]	1.3	0.23 ± 0.04[17]	0.26		9.7		3.9
^{206}Pb	1.20 ± 0.20[18] 1.06 ± 0.26[29]	1.2	0.32 ± 0.04[29] 0.13[25]	0.37	9.46 ± 0.15[29]	7.2		5.0

[16–18] and original papers [21–32]. Tables 2 and 3 show that our approach allows to describe those values sufficiently well. For example, while the isotopic dependence of S_0 for the Te isotopes was not described before, our approach allowed to describe it. Another interesting example present isotopes $^{112-124}$Sn which are located around the maximum of the p-wave and the minimum of s- and d-wave neutron strength functions. Therefore the p-wave contributions to neutron cross sections are dominant here, and that favours experimental determination of S_1 [23]. At the same time the experimental values of S_0 for the isotopes of Sn are very small [24], and this fact leads to serious difficulties in the description of S_0 for these isotopes (see e.g. [16]), but in our approach such a description seems to be quite satisfactory (see Table 2).

Note that one of the difficulties in a model description of the neutron strength functions for some nuclei is connected with rather big dispersion of their values extracted from experimental data at different energies. Taking this fact into account allows to remove (or at least to reduce) some discrepancies between calculated and experimental values of the strength functions under consideration. For example, while all the theoretical values of S_l presented in Tables 2 and 3 are calculated at $E_n = 40\,\text{keV}$, for several nuclei we give two S_1 values calculated at 40 and 700 keV, and the latters agree with the data of [23].

Table 3 also demonstrates a satisfactory agreement between calculated and experimental values of d-wave neutron strength functions for $^{112-124}$Sn [23], ^{144,148}Sm [29], and ^{206}Pb [25], i.e. for the nuclei which we can consider in our approach (most of the available data on d-wave strength functions concern the deformed nuclei). Results of our calculation confirm the well-known assumption that d-wave neutron strength functions are approximately equal to the s-wave ones.

Table 3. d-wave neutron strength functions

Nucleus	$S_2 \times 10^4$ exp.	$S_2 \times 10^4$ theor.
^{112}Sn	0.3 ± 0.1[23]	0.25
^{114}Sn	0.2 ± 0.1[23]	0.17
^{116}Sn	0.20 ± 0.04[23]	0.25
^{118}Sn	0.16 ± 0.05[23]	0.20
^{120}Sn	0.14 ± 0.02[23]	0.19
^{122}Sn	0.17 ± 0.05[23]	0.22
^{124}Sn	0.15 ± 0.08[23]	0.21
^{144}Sm	2.33 ± 0.44[29]	2.01
^{148}Sm	3.50 ± 0.46[29]	3.10
^{206}Pb	1.5[25]	1.64

Thus, the model used here allows to describe neutron strength functions and potential lengths for even-even spherical nuclei reasonably well.

4 N_pN_n systematics of the neutron inelastic cross sections

In [5] an attempt was made to systematize experimental cross sections of inelastic neutron scattering with the 2_1^+ level exitation for even-even nuclei. The inelastic neutron cross section values were considered as a function of valence nucleon numbers. It was shown by Casten [10] that different quantities characterizing the collective nuclear properties can be presented as smooth functions of the product N_pN_n (N_p and N_n are numbers of valence protons and neutrons or their hole states). The values of N_pN_n for many even-even spherical nuclei with $60 \leq A \leq 206$ are given in Table 1 taking into account the existence of non-traditional magic (or semimagic) numbers of nucleons.

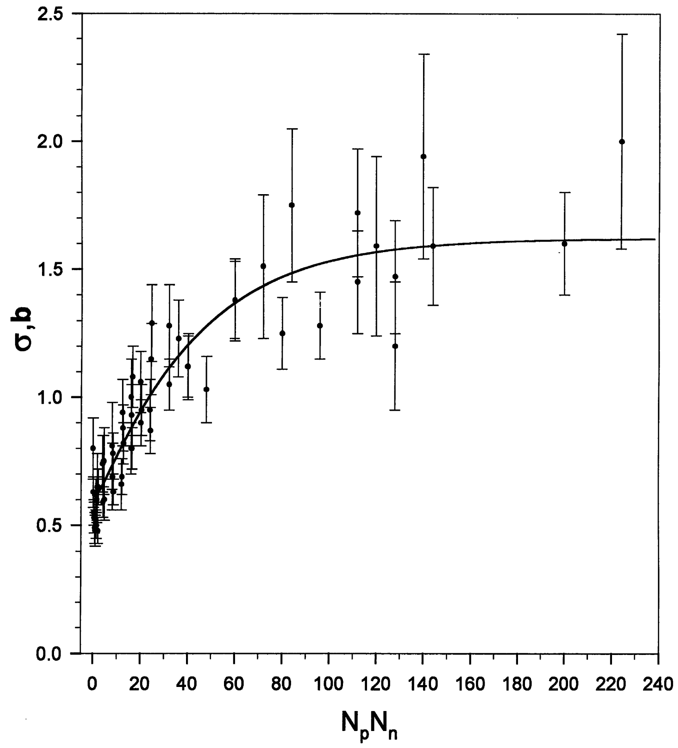

Fig. 5. Inelastic neutron cross sections with 2_1^+ level excitation at the energy of 300 MeV over threshold *vs.* the N_pN_n product. The solid line is drawn using the least square method

Experimental cross section values of neutron inelastic scattering with 2_1^+ level exitation for the energy equal to 300 keV over the threshold are plotted on Fig. 5 *vs.* N_pN_n (we used here cross section values averaged over the energy range of 100 keV). Note that for the N_pN_n systematics of neutron inelastic scattering we consider relevant cross section values for deformed nuclei as well as for spherical ones. Within the experimental errors all these cross sections show more or less smooth dependence on the product N_pN_n. On the average, this dependence is described by the solid curve of Fig. 5 which is drawn using the least square method (with $\chi^2 \lesssim 1$ per one point).

The smoothness of this dependence to a great extent is due to taking into account the effect of appearance (and disappearance) of semimagic numbers of nucleons. For instance, the N_pN_n values for neighbouring isotopes ^{70}Ge and ^{72}Ge are equal to 0 and 40 respectively, the corresponding points on the plot of Fig. 5 are located rather far one from the other, and as a result they do not break the smoothness of the curve under consideration (in spite of the fact that the relevant cross sections differ one from the other by factor of 1.7). It is known that semimagic numbers are less stable than the traditional magic ones; two isotopes of Ge illustrate this property for the semimagic number $N = 38$.

The existence of the semimagic number $Z = 38$ (or 40) [33] and its disappearence due to the monopole interaction of valence proton and neutron (filling $g_{9/2}$ and $g_{7/2}$ states) should be taken into account while analysing properties of the Mo isotopes [5]. Similar conclusions can be made concerning to semimagic $Z = 64$ and $N = 64$ [10]: their existence (and disappearence) is also confirmed by the analysis of neutron inelastic scattering on the isotopes of Sm and Cd in the framework of the N_pN_n systematics [5,6].

It is seen from Fig. 5 that the smooth increase of the inelastic cross sections practically stops for $N_pN_n \gtrsim 60$, which corresponds to considerable deformations. For example, the relevant cross section for ^{238}U ($N_pN_n = 200$) [34] coincides with the cross sections for the W isotopes shown on Fig. 5. Such a behaviour seems to be quite natural since this product can be regarded as a quantity connected with the collectivity degree of low-lying nuclear states.

5 Conclusion

Thus, our calculations of neutron cross sections for even-even spherical nuclei in the framework of CCOM show that the two-phonon version of this model allows to obtain a unified description of neutron data for these nuclei at neutron energies $E_n < 3\,\text{MeV}$ including total, elastic and inelastic cross sections, angular distributions of elastically and inelastically scattered neutrons, strength functions and potential scattering lengths. Such a description was obtained using one set of the model parameters, but assuming that the surface layer thickness (diffuseness of the optical potential) may be slightly altered for magic and near-magic nuclei.

Our results show that this version of CCOM can be used for calculating neutron cross sections and strength functions of even-even spherical nuclei for which direct measurements of these quantities are impossible or difficult.

As to the N_pN_n-systematics of inelastic neutron cross sections, being combined with CCOM calculations it presents an additional method of finding so-called semimagic numbers of protons and neutrons.

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