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SHELL MODEL ANALYSIS OF $N = 82$ ISOTONES ABOVE ^{132}Sn*

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Nuclei with up to 6 protons added to ^{132}Sn are described within a truncated shell model basis formed by the proton orbits $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$ and $0h_{11/2}$. Single-particle energies and two-body interaction matrix elements are determined from experimental excitation energies in ^{133}Sb and ^{134}Te. These parameters are then used for calculating levels in ^{135}I, ^{136}Xe, ^{137}Cs and ^{138}Ba. The calculated energies agree well with experimental values in these 4 nuclei.

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1. Introduction

The shell model forms the standard basis for the description of spherical nuclei. It gives in general a good representation of the nuclear structure in doubly-magic regions.

In such a nucleus the states at low excitation energy are formed by the motion of a few valence nucleons in a small number of orbits, while the doubly-magic core largely remains in its ground state. As the excitation energy increases the core can become excited, and eventually at high energy the degrees of freedom of the core nucleons and the valence nucleons become thoroughly mixed.

In the low-energy regime the individual energy eigenstates are well approximated by solutions to a Schroedinger equation involving explicitely only the degrees of freedom of the valence nucleons. The core manifests itself not only through the static mean field which determines the main part of the single-particle energies, but also dynamically by polarization effects on both the single-particle energies and the effective two-nucleon interaction.

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Large efforts have been devoted to a program of deriving the one- and two-body terms in the shell model Hamiltonian from the basic bare nucleon-nucleon interaction. Considerable progress has been made in this approach. The single-particle energies calculated in such a way are however not accurate enough to allow one to exploit fully the power of the shell model. Therefore one usually prefers to use instead empirical single-particle energies, obtained from experimental energies of states in nuclei with a single valence nucleon.

The effective two-nucleon interaction derived from many-body theory can be used directly in shell model calculations. The agreement with experimental energies and other properties is often satisfactory [1, 2], but the intrinsic accuracy of the shell model is not always fully exploited.

An alternative approach is to use instead an empirical two-nucleon interaction, in the same spirit as one uses empirical single-particle energies, but now determined from the properties of levels in nuclei with two valence nucleons. In principle, all the interaction matrix elements are determined if one has complete knowledge of the states in the two-valence-particle nucleus, i.e. not only the energies but also the composition of the wave functions of all levels in a given configuration basis.

This extreme approach does not work in practice, since the experimental information about configuration mixing from spectroscopic factors and electromagnetic transition rates is always incomplete. If configuration mixing is not very strong a diagonal interaction matrix element is well determined by the energy of the corresponding state, but usually only few of the non-diagonal matrix elements are strongly constrained by experimental data. This situation points to a hybrid approach, combining the two methods, where one starts from a complete set of theoretical matrix elements and adjusts those which are sensitive to experimental data.

2. The $N = 82$ isotones above ^{132}Sn

^{132}Sn shows strong shell closures of both protons at $Z = 50$ and neutrons at $N = 82$. The lowest core excitations come in only above 4 MeV. For nuclei near ^{132}Sn one can therefore expect that states up to a considerable excitation energy can be described by wave functions representing the motion of the valence nucleons only.

Shell model calculations are easier to perform if there is only one kind of valence nucleon, both because the size of the configuration space is smaller, and because one only needs to know one like-particle interaction. For this reason many calculations in heavy nuclei have been limited to singly-closed-shell nuclei. Since ^{132}Sn is a neutron rich nucleus most experimental information exists about its neighbours with more neutrons and/or fewer protons.

Recently shell model calculations with modern G-matrix interactions have been performed both for $N = 82$ isotones above ^{132}Sn [3, 4] and for $Z = 50$ isotopes to the left of ^{132}Sn [5]. In both cases the model space included the five orbits $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$ and $0h_{11/2}$ which make up the major shell between 50 and 82.

In an extended sequence of studies of the $N = 82$ isotones [6] Wildenthal has used the alternative approach mentioned above. He starts from a simple surface-delta plus quadrupole-quadrupole interaction and then changes a number of combinations of two-nucleon matrix elements in order to fit as well as possible known excitation energies in nuclei all the way up to ^{154}Hf. Some controlled matrix truncations had to be made for the heavier nuclei with more than 6 valence protons. Wildenthal's final matrix elements are listed in column 3 of Table II.

3. The present calculation

Recently new experimental information has appeared about levels in the single-proton nucleus ^{133}Sb [7] and the two-proton nucleus ^{134}Te [8–10]. The new data constrains some important matrix elements more strongly than older data. This has motivated our attempt to make an improved shell model calculation for the $N = 82$ isotones near ^{132}Sn.

The experimental energies of the 4 known single-proton states in ^{133}Sb have been used in the calculation without further adjustment. The fifth state $2s_{1/2}$ has not been observed in ^{133}Sb. Its energy was left as a free parameter. It is mainly determined by the fit to the known $s_{1/2}$ one-quasiparticle state in ^{137}Cs at 2150 keV.

TABLE I

Single-particle energies (keV).

#	nlj	ε
1	$0g_{7/2}$	0
2	$1d_{5/2}$	962
3	$1d_{3/2}$	2439
4	$2s_{1/2}$	2920
5	$0h_{11/2}$	2793

There are 160 matrix elements of the two-body interaction in the $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, $s_{1/2}$, $H_{11/2}$ basis. The values of Wildenthal [6] were used as a starting point in the fit. Known two-proton levels in ^{134}Te [8–10] determined 18 diagonal matrix involving the $g_{7/2}$, $d_{5/2}$ and $h_{11/2}$ shells. Additional adjustments of 36 matrix elements helped to improve the fit to known level energies in ^{135}I, ^{136}Xe, ^{137}Cs and ^{138}Ba. The resulting matrix elements are given in column 4 of Table II. The quality of the fit is shown in Table III. It may be noted that the states with $J > 11/2$ in ^{137}Cs had not been observed at the time of the calculation and were therefore not considered in the fit.

TABLE II

Two-body interaction matrix elements (keV)

a b c d	J	Wild	adj.	a b c d	J	Wild	adj.
1 1 1 1	0	-525.6	-448	1 2 2 3	1	- 7.0	
	2	+108.4	+130		2	+145.7	
	4	+372.6	+376		3	-166.0	
	6	+466.2	+486		4	+292.9	
1 1 1 2	2	+133.2	0	1 2 2 4	2	+ 48.0	
	4	+ 87.7	+100		3	- 19.7	
	6	- 17.7	+200	1 2 3 3	2	- 36.1	
1 1 1 3	2	-317.7	-200	1 2 3 4	1	-158.6	
	4	-164.1	- 50		2	-167.9	
1 1 1 4	4	+116.3		1 2 5 5	2	-120.5	
1 1 2 2	0	-902.6	-800		4	-136.5	
	2	-118.4	-150		6	-184.0	
	4	- 31.3	0	1 3 1 3	2	- 83.7	+100
1 1 2 3	2	-133.2			3	+484.2	+600
	4	-196.7			4	+337.2	+500
1 1 2 4	2	-121.9			5	+496.8	+710
1 1 3 3	0	-663.0		1 3 1 4	3	- 90.2	
	2	-263.4			4	+215.3	
1 1 3 4	2	+162.6		1 3 2 2	2	-138.3	
1 1 4 4	0	-400.7			4	-121.7	
1 1 5 5	0	+867.7	+1100	1 3 2 3	2	-118.5	
	2	+228.3			3	+ 79.2	
	4	+159.1			4	-303.0	
	6	+ 94.7		1 3 2 4	2	-327.6	
1 2 1 2	1	+465.9	+427		3	+ 46.1	
	2	+418.8	+398	1 3 3 3	2	-286.5	
	3	+516.0	+530	1 3 3 4	2	+391.7	
	4	+324.6	+429	1 3 5 5	2	+375.0	
	5	+437.7	+524		4	+147.6	
	6	+136.0	+ 91	1 4 1 4	3	+441.0	
1 2 1 3	2	+107.1	+200		4	+256.8	
	3	+ 76.2	0	1 4 2 2	4	+134.1	
	4	+ 63.0	+100	1 4 2 3	3	+ 14.1	
	5	+ 55.2	+100		4	+270.5	
1 2 1 4	3	- 68.3		1 4 2 4	3	+ 2.3	
	4	-216.7	-100	1 4 5 5	4	-178.3	
1 2 2 2	2	+118.0	+200	1 5 1 5	2	+160.0	0
	4	+ 54.7	+100		3	+154.9	+200

a b c d	J	Wild	adj.	a b c d	J	Wild	adj.
1 5 1 5	4	+285.3	+500	2 4 2 4	2	+ 88.5	
	5	+328.1	+368		3	+434.9	
	6	+498.6	+463	2 4 3 3	2	-252.8	
	7	+403.8	+288	2 4 3 4	2	+333.4	
	8	+475.0	+531	2 4 5 5	2	+333.2	
	9	- 51.9	- 27	2 5 2 5	3	-452.1	0
1 5 2 5	3	+176.5	+100		4	+302.9	+300
	4	+ 40.3			5	+263.6	0
	5	+186.2			6	+629.7	+435
	6	+ 7.9			7	+518.1	+155
	7	+ 92.3	0		8	+366.1	+796
	8	- 98.2		2 5 3 5	4	- 59.4	
1 5 3 5	4	- 50.7			5	+ 98.8	
	5	-156.9			6	+ 1.4	
	6	- 77.2			7	+196.9	
	7	-251.1		1 5 4 5	5	-283.7	
1 5 4 5	5	+130.6			6	- 49.2	
	6	- 1.3		3 3 3 3	0	-110.1	
2 2 2 2	0	-339.5	-150		2	+440.3	
	2	+255.0	+150	3 3 3 4	2	+209.1	
	4	+174.0	+260	3 3 4 4	0	-466.4	
2 2 2 3	2	+100.3		3 3 5 5	0	+697.2	
	4	-272.8			2	+201.6	
2 2 2 4	2	-232.5		3 4 3 4	1	+587.6	
2 2 3 3	0	-436.4			2	+302.7	
	2	- 81.1		3 4 5 5	2	-296.9	
2 2 3 4	2	+213.8		3 5 3 5	4	+310.4	
2 2 4 4	0	-515.9			5	+352.3	
2 2 5 5	0	+643.7	+900		6	+495.9	
	2	+173.6			7	+ 42.8	
	4	+ 91.8		3 5 4 5	5	+300.5	
2 3 2 3	1	+299.7			6	- 37.3	
	2	+334.8		4 4 4 4	0	+231.9	
	3	+564.5		4 4 5 5	0	+527.5	
	4	+155.2		4 5 4 5	5	+165.1	
2 3 2 4	2	-224.9			6	+464.2	
	3	+ 8.7		5 5 5 5	0	-1114.4	
2 3 3 3	2	-135.1			2	-116.3	
2 3 3 4	1	+ 1.1			4	+147.2	0
	2	+180.3			6	+317.4	+200
2 3 5 5	2	+170.6			8	+369.3	+300
	4	+207.9			10	+433.3	+400

TABLE III

Comparison of experimental and calculated energies (keV).

	^{135}I				^{136}Xe		
J #	Exp	Calc	E-C	J #	Exp	Calc	E-C
3/2+ 1	1010	1011	- 1	0+ 1	0	15	-15
5/2+ 1	603	623	-20	2	2582	2571	+11
2	870	844	+26	3	2849	2838	+11
3	1857	1888	-31	1+ 1	2634	2593	+40
7/2+ 1	0	-11	+11	2+ 1	1313	1372	-59
2	1710	1704	+ 6	2	2290	2295	- 5
9/2+ 1	1184	1196	-12	3	2415	2446	-31
11/2+ 1	1134	1144	-10	3+ 1	2560	2539	+21
15/2+ 1	1422	1414	+ 8	4+ 1	1694	1717	-23
17/2+ 1	1994	1978	+16	2	2126	2155	-29
19/2- 1	3655	3680	-25	3	2465	2465	0
21/2- 1	3766	3775	- 9	5+ 1	2444	2448	- 4
23?2- 1	3689	3676	+13	2	2608	2579	+29
				6+ 1	1892	1858	+34
				2	2262	2236	+26
				8+ 1	2866	2862	+ 4
				2	3229	3242	-13
				10+ 1	3484	3484	0
				9- 1	3830	3840	-10
				11- 1	4857	4923	-66
				13- 1	5142	5138	+ 4
	^{137}Cs				^{138}Ba		
1/2+ 2	2150	2135	+15	0+ 1	0	-5	+ 5
3/2+ 4	2068	2066	+ 2	2	2190	2092	+98
5/2+ 1	455	387	+68	1+ 1	2583	2574	+ 9
2	849	907	-58	2+ 1	1436	1485	-49
3	1651	1670	-19	2	2218	2181	+37
7/2+ 1	0	-15	+15	3	2640	2542	+98
2	1575	1576	- 1	3+ 1	2446	2368	+78
3	1783	1810	-27	4+ 1	1899	1913	-14
9/2+ 1	1273	1320	-47	2	2308	2291	+17
2	1570	1549	+21	3	2583	2637	-54
3	1916	1916	0	4	2779	2787	- 8
11/2+ 1	1185	1223	-38	5+ 1	2415	2307	+108
15/2+ 1	1671	1642	+29	6+ 1	2091	2046	+45
17/2+ 1	1894	1879	+15	2	2203	2184	+19
21/2+ 1	2784	2827	-43	7+ 1	3309	3344	-35
23/2+ 1	3464	3462	+ 2	8+ 1	3184	3200	-16
11/2- 1	1868	1836	+32	2	3610	3611	- 1
23/2- 1	3496	3503	- 7	9+ 2	4158	4108	+50
27/2- 1	4408	4424	-16	10+ 1	3622	3646	-24
29/2- 1	5023	5007	+16	2	3911	3879	+32
31/2- 1	5494	5492	+ 2	12+ 1	4689	4724	-35
				8- 1	3678	3631	+47
				9- 1	3633	3648	-15

4. Summary

Nuclei with a few protons added to the closed core nucleus ^{132}Sn have been calculated by a standard shell model diagonalization in the full model space spanned by the proton orbits $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$ and $0h_{11/2}$. An empirical effective interaction has been designed, which gives a good representation of experimental level energies in ^{133}Sb, ^{134}Tb, ^{135}I, ^{136}Xe, ^{137}Cs and ^{138}Ba. New experimental energies of two-proton levels in ^{134}Te were essential in constraining the effective interaction. The quality of the fit is still inferior to that obtained by similar calculations in the region of ^{208}Pb. This indicates that the intrinsic accuracy of the model is not exhausted. Further improvement would be facilitated by additional experimental data in the $N = 82$ isotones immediately above ^{132}Sn.

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