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 explicitly 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 nucleonnucleon 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 nondiagonal 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 ¹³²Sn

 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 ¹³²Sn 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 ¹³²Sn [3,4] and for Z = 50isotopes 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 ¹³²Sn.

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 ¹³³Sb. 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

Sing	le-pa	rticle ene	ergies (k	eV).
	#	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 ¹³⁴Te [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 ¹³⁵I, ¹³⁶Xe, ¹³⁷Cs and ¹³⁸Ba. 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 ¹³⁷Cs had not been observed at the time of the calculation and were therefore not considered in the fit. TABLE II

a b c d	J	Wild	adj.	a b c d	J	Wild	adj.
1111	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

Two-body interaction matrix elements (keV)

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	0
	5	+328.1	+368		3	+434.9	
	6	+498.6	+463	$2\ 4\ 3\ 3$	2	-252.8	
	$\overline{7}$	+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	2525	3	-452.1	0
1525	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		2535	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		1545	5	-283.7	
$1\ 5\ 4\ 5$	5	+130.6			6	- 49.2	
	6	- 1.3		3333	0	-110.1	
$2\ 2\ 2\ 2\ 2$	0	-339.5	-150		2	+440.3	
	2	+255.0	+150	3334	2	+209.1	
0 0 0 0	4	+174.0	+260	3344	0	-466.4	
2223	2	+100.3		3333	บ ถ	+097.2	
0004	4	-272.8 020 5		9494	2	+201.0	
44 0000	4	-232.0 496-4		3434	1 0	+301.0	
2200	0	-430.4		2155	2	+302.7	
2224	∠ ?	- 01.1		0400 3535	2 4	-290.9	
2234 2244	0	-515.0		0000	5	± 310.4 ± 352.3	
2244	0	± 643.7	0 00		6	± 405.0	
2200	2	+173.6	1 300		7	+42.8	
	4	+ 91.8		3545	5	+300.5	
2323	1	+299.7		0010	6	- 37.3	
2020	2	+334.8		4444	Ő	+231.9	
	3	+564.5		4455	Ő	+527.5	
	4	+155.2		4545	$\tilde{5}$	+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

Comparison of experimenta	l and calculated	energies (keV).
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	195				196		
	^{135}I				¹³⁶ Xe		
J #	Exp	Calc	E-C	J #	Exp	Calc	E-C
$3/2+$ $\overline{1}$	1010	1011	- 1	$0+$ $\overline{1}$	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
	137Cm_{\odot}				138 D.		
1/9 - 9	$\frac{^{137}\text{Cs}}{^{2150}}$	9125	+ 15	0 + 1	¹³⁸ Ba	5	- 5
$\frac{1}{2+2}$	$\frac{^{137}\mathrm{Cs}}{2150}$	2135	+15	$0+ \ 1 \ 2$	¹³⁸ Ba 0 2100	-5	+5
1/2+2 3/2+4 5/2+1		$2135 \\ 2066 \\ 287$	+15 + 2 + 68	0+1 2 1+1		-5 2092 2574	+5 + 98 + 98
$1/2+2 \ 3/2+4 \ 5/2+1 \ 2$		2135 2066 387	$^{+15}_{+2}_{+68}_{58}$	$0+1 \\ 2 \\ 1+1 \\ 2+1$	$ \begin{array}{r} 138 \text{Ba} \\ 0 \\ 2190 \\ 2583 \\ 1426 \end{array} $	-5 2092 2574	+5 + 98 + 9 + 9 + 40
$1/2+2 \\ 3/2+4 \\ 5/2+1 \\ 2 \\ 2$	$\begin{array}{r}^{137}\mathrm{Cs}\\2150\\2068\\455\\849\\1651\end{array}$	2135 2066 387 907 1670	$^{+15}_{+2}_{+68}_{-58}$	$egin{array}{c} 0+1\ 2\ 1+1\ 2+1\ 2\end{array}$	$ \begin{array}{r} {}^{138}\text{Ba} \\ 0 \\ 2190 \\ 2583 \\ 1436 \\ 2218 \end{array} $	-5 2092 2574 1485 2181	+5 + 98 + 9 - 49 - 49 + 37
$ \begin{array}{r} 1/2+2 \\ 3/2+4 \\ 5/2+1 \\ 2 \\ 3 \\ 7/2+1 \end{array} $	$\begin{array}{r}^{137}\mathrm{Cs}\\2150\\2068\\455\\849\\1651\\0\end{array}$	$2135 \\ 2066 \\ 387 \\ 907 \\ 1670 \\ 15$	+15 + 2 +68 -58 -19 + 15	$egin{array}{cccc} 0+1 & 2 & \ 1+1 & 2+1 & \ 2+2 & 2 & \ 2 & 2 & \ \end{array}$	$ \begin{array}{r} {}^{138}\text{Ba} \\ 0 \\ 2190 \\ 2583 \\ 1436 \\ 2218 \\ 2640 \end{array} $	-5 2092 2574 1485 2181 2542	+5 + 98 + 9 - 49 + 37 + 08
$ \begin{array}{r} 1/2+2 \\ 3/2+4 \\ 5/2+1 \\ 2 \\ 3 \\ 7/2+1 \\ 2 \end{array} $	${}^{137}Cs$ 2150 2068 455 849 1651 0 1575	$2135 \\ 2066 \\ 387 \\ 907 \\ 1670 \\ -15 \\ 1576$	+15 + 2 + 68 -58 -19 + 15 1	$0+1 \\ 2 \\ 1+1 \\ 2+1 \\ 2 \\ 3 \\ 2+1$	$\begin{array}{r}{}^{138}\mathrm{Ba}\\\\0\\2190\\2583\\1436\\2218\\2640\\2446\end{array}$	-5 2092 2574 1485 2181 2542 2268	+5 + 98 + 9 - 49 + 37 + 98 + 78
$ \begin{array}{r} 1/2+2 \\ 3/2+4 \\ 5/2+1 \\ 2 \\ 3 \\ 7/2+1 \\ 2 \\ 2 \\ 2 \end{array} $	$\begin{array}{r}^{137}\mathrm{Cs}\\2150\\2068\\455\\849\\1651\\0\\1575\\17^{\circ}2\end{array}$	2135 2066 387 907 1670 -15 1576 1810	+15 + 2 +68 -58 -19 +15 - 1 27	0+1 2 1+1 2+1 2 3 3+1 4+1	¹³⁸ Ba 0 2190 2583 1436 2218 2640 2446 1800	-5 2092 2574 1485 2181 2542 2368 1012	+5 + 98 + 9 -49 + 37 + 98 + 78 + 78 + 78 + 78 + 74 + 78 + 78 + 7
$ \begin{array}{r} 1/2+2 \\ 3/2+4 \\ 5/2+1 \\ 2 \\ 3 \\ 7/2+1 \\ 2 \\ 3 \\ 0/2+1 \end{array} $	$\begin{array}{r} {}^{137}\mathrm{Cs}\\ 2150\\ 2068\\ 455\\ 849\\ 1651\\ 0\\ 1575\\ 1783\\ 1272\end{array}$	$\begin{array}{r} 2135\\ 2066\\ 387\\ 907\\ 1670\\ -15\\ 1576\\ 1810\\ 1220 \end{array}$	+15 + 2 + 68 -58 -19 + 15 - 1 -27 47	$egin{array}{c} 0+1 & 2 \ 1+1 & 2 \ 2+1 & 2 \ 3 & 3+1 & 4+1 \ 4+1 & 2 \end{array}$	$\begin{array}{r} {}^{138}\mathrm{Ba} \\ \hline 0 \\ 2190 \\ 2583 \\ 1436 \\ 2218 \\ 2640 \\ 2446 \\ 1899 \\ 2208 \end{array}$	-5 2092 2574 1485 2181 2542 2368 1913 2201	+5 +98 +9 -49 +37 +98 +78 -14
$ \begin{array}{r} 1/2+2 \\ 3/2+4 \\ 5/2+1 \\ 2 \\ 3 \\ 7/2+1 \\ 2 \\ 3 \\ 9/2+1 \\ 2 \\ 3 \\ 9/2+2 \\ 2 \\ 3 \\ 9/2+2 \\ 2 \\ 3 \\ 9/2+2 \\ 2 \\ 3 \\ 9/2+2 \\ 2 \\ 3 \\ 9/2+2 \\ 2 \\ 3 \\ 9/2+2 \\ 3 \\ 3 \\ 9/2+2 \\ 3 \\ 3 \\ 3 \\ 9/2+2 \\ 3 \\ 3 \\ 9/2+2 \\ 3 \\ 3 \\ 3 \\ 9/2+2 \\ 3 \\ $	${}^{137}Cs$ 2150 2068 455 849 1651 0 1575 1783 1273 1570	$\begin{array}{c} 2135\\ 2066\\ 387\\ 907\\ 1670\\ -15\\ 1576\\ 1810\\ 1320\\ 1540 \end{array}$	+15 + 2 + 68 -58 -19 + 15 - 1 -27 -47 + 21	$egin{array}{cccc} 0+1&&&&&\\ 1+1&&&&&\\ 2+1&&&&&\\ 2&&&&&\\ 3+1&&&&&\\ 4+1&&&&&\\ 2&&&&&\\ 2&&&&&\\ \end{array}$	${}^{138}\text{Ba} \\ 0 \\ 2190 \\ 2583 \\ 1436 \\ 2218 \\ 2640 \\ 2446 \\ 1899 \\ 2308 \\ 2582 \\ 2$	-5 2092 2574 1485 2181 2542 2368 1913 2291 2627	+5 +98 +9 -49 +37 +98 +78 -14 +17
$ \begin{array}{r} 1/2+2 \\ 3/2+4 \\ 5/2+1 \\ 2 \\ 3 \\ 7/2+1 \\ 2 \\ 3 \\ 9/2+1 \\ 2 \\ 2 \\ 2 \end{array} $	$\begin{array}{r} {}^{137}\mathrm{Cs}\\ \hline 2150\\ 2068\\ 455\\ 849\\ 1651\\ 0\\ 1575\\ 1783\\ 1273\\ 1570\\ 1016\end{array}$	$\begin{array}{c} 2135\\ 2066\\ 387\\ 907\\ 1670\\ -15\\ 1576\\ 1810\\ 1320\\ 1549\\ 1016\end{array}$	+15 + 2 + 68 -58 -19 + 15 - 1 -27 -47 + 21 - 20 - 20 - 20 - 20 - 20 - 20 - 20 -	$egin{array}{cccc} 0+1&&&&&&\\ 1+1&&&&&&\\ 2+1&&&&&&\\ 2&&&&&&&\\ 3&+1&&&&&&\\ 4+1&&&&&&&\\ 2&&&&&&&&\\ 3&&&&&&&&\\ 3&&&&&&&&\\ &&&&&&&&$	¹³⁸ Ba 0 2190 2583 1436 2218 2640 2446 1899 2308 2583 2770	-5 2092 2574 1485 2181 2542 2368 1913 2291 2637 2787	+5 +98 +9 -49 +37 +98 +78 -14 +17 -54
$ \begin{array}{r} 1/2+2 \\ 3/2+4 \\ 5/2+1 \\ 2 \\ 3 \\ 7/2+1 \\ 2 \\ 3 \\ 9/2+1 \\ 2 \\ 3 \\ 11/2+1 \end{array} $	${}^{137}Cs$ 2150 2068 455 849 1651 0 1575 1783 1273 1570 1916 1185	2135 2066 387 907 1670 -15 1576 1810 1320 1549 1916 1222	+15 + 2 + 68 -58 -19 + 15 - 1 -27 -47 + 21 0 28	0+1 2 1+1 2+1 2 3 3+1 4+1 2 3 4 5+1	¹³⁸ Ba 0 2190 2583 1436 2218 2640 2446 1899 2308 2583 2779 2415	-5 2092 2574 1485 2181 2542 2368 1913 2291 2637 2787 2787	+5 +98 +9 -49 +37 +98 +78 -14 +17 -54 -8
$ \begin{array}{r} 1/2+2 \\ 3/2+4 \\ 5/2+1 \\ 2 \\ 3 \\ 7/2+1 \\ 2 \\ 3 \\ 9/2+1 \\ 2 \\ 3 \\ 11/2+1 \\ 15/2+1 \end{array} $	${}^{137}Cs$ 2150 2068 455 849 1651 0 1575 1783 1273 1570 1916 1185 1671	2135 2066 387 907 1670 -15 1576 1810 1320 1549 1916 1223 1642	+15 + 2 + 68 -58 -19 + 15 - 1 -27 -47 + 21 0 -38 + 22	$0+1 \\ 2 \\ 1+1 \\ 2+1 \\ 2 \\ 3 \\ 3+1 \\ 4+1 \\ 2 \\ 3 \\ 4 \\ 5+1 \\ 6+1 \\ 1 \\ 1 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5+1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\$	¹³⁸ Ba 0 2190 2583 1436 2218 2640 2446 1899 2308 2583 2779 2415 2001	-5 2092 2574 1485 2181 2542 2368 1913 2291 2637 2787 2307 2046	+5 +98 +9 -49 +37 +98 +78 -14 +17 -54 -8 +108
$\begin{array}{c} 1/2+2\\ 3/2+4\\ 5/2+1\\ 2\\ 3\\ 7/2+1\\ 2\\ 3\\ 9/2+1\\ 2\\ 3\\ 11/2+1\\ 15/2+1\\ 15/2+1\\ 17/0+1\end{array}$	$\begin{array}{r} {}^{137}\mathrm{Cs}\\ \hline 2150\\ 2068\\ 455\\ 849\\ 1651\\ 0\\ 1575\\ 1783\\ 1273\\ 1570\\ 1916\\ 1185\\ 1671\\ 1804\end{array}$	$\begin{array}{c} 2135\\ 2066\\ 387\\ 907\\ 1670\\ -15\\ 1576\\ 1810\\ 1320\\ 1549\\ 1916\\ 1223\\ 1642\\ 1872\end{array}$	+15 + 2 + 68 -58 -19 + 15 - 1 -27 -47 + 21 0 -38 + 29 + 15	$0+1\ 2\ 1+1\ 2+1\ 2\ 3\ 3+1\ 4+1\ 2\ 3\ 4\ 5+1\ 6+1\ 2$	¹³⁸ Ba 0 2190 2583 1436 2218 2640 2446 1899 2308 2583 2779 2415 2091	-5 2092 2574 1485 2181 2542 2368 1913 2291 2637 2787 2007 2006	+5 +98 +9 -49 +37 +98 +78 -14 +17 -54 -8 +108 +45 +12
$ \begin{array}{r} 1/2+2 \\ 3/2+4 \\ 5/2+1 \\ 2 \\ 3 \\ 7/2+1 \\ 2 \\ 3 \\ 9/2+1 \\ 2 \\ 3 \\ 11/2+1 \\ 15/2+1 \\ 17/2+1 \\ 17/2+1 \\ 17/2+1 \\ 21/2+1 \\ 17/2+1 \\ 3/2+1 \\ 17/2+1 \\ $	${}^{137}Cs$ 2150 2068 455 849 1651 0 1575 1783 1273 1570 1916 1185 1671 1894 2724	2135 2066 387 907 1670 -15 1576 1810 1320 1549 1916 1223 1642 1879	+15 + 2 + 68 -58 -19 +15 -1 -27 -47 +21 0 -38 +29 +15 -42 +21 -38 +29 +15 +22 +21 -38 +22 +23 +23 +23 +23 +23 +23 +23 +23 +23	$0+1 \\ 2 \\ 1+1 \\ 2+1 \\ 2 \\ 3 \\ 3+1 \\ 4+1 \\ 2 \\ 3 \\ 4 \\ 5+1 \\ 6+1 \\ 2 \\ 7+1 \\ 1 \\ 2 \\ 7+1 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5+1 \\ 1 \\ 2 \\ 7+1 \\ 1 \\ 2 \\ 1 \\ 1 \\ 1 \\ 2 \\ 1 \\ 1 \\ 1 \\ $	¹³⁸ Ba 0 2190 2583 1436 2218 2640 2446 1899 2308 2583 2779 2415 2091 2203	-5 2092 2574 1485 2181 2542 2368 1913 2291 2637 2787 2307 2046 2184	+5 +98 +9 +37 +98 +78 -14 +17 -54 -8 +108 +45 +19
$\begin{array}{c} 1/2+2\\ 3/2+4\\ 5/2+1\\ 2\\ 3\\ 7/2+1\\ 2\\ 3\\ 9/2+1\\ 2\\ 3\\ 11/2+1\\ 15/2+1\\ 17/2+1\\ 21/2+1\\ 21/2+1\\ 21/2+1\end{array}$	$\begin{array}{r} {}^{137}\mathrm{Cs}\\ \hline 2150\\ 2068\\ 455\\ 849\\ 1651\\ 0\\ 1575\\ 1783\\ 1273\\ 1570\\ 1916\\ 1185\\ 1671\\ 1894\\ 2784\\$	2135 2066 387 907 1670 -15 1576 1810 1320 1549 1916 1223 1642 1879 2827	$\begin{array}{r} +15 \\ +2 \\ +68 \\ -58 \\ -19 \\ +15 \\ -1 \\ -27 \\ -47 \\ +21 \\ 0 \\ -38 \\ +29 \\ +15 \\ -43 \\ -43 \end{array}$	$egin{array}{ccccc} 0+1&&&&2\ 1+1&2+1&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&$	¹³⁸ Ba 0 2190 2583 1436 2218 2640 2446 1899 2308 2583 2779 2415 2091 2203 3309	-5 2092 2574 1485 2181 2542 2368 1913 2291 2637 2787 2307 2046 2184 3344 3220	+5 +98 +9 -49 +37 +98 +78 -14 +17 -54 -8 +108 +45 +19 -35
$\begin{array}{c} 1/2+2\\ 3/2+4\\ 5/2+1\\ 2\\ 3\\ 7/2+1\\ 2\\ 3\\ 9/2+1\\ 2\\ 3\\ 11/2+1\\ 15/2+1\\ 15/2+1\\ 17/2+1\\ 21/2+1\\ 21/2+1\\ 23/2+1\\ 23/2+1\\ 21/2+1\\ 23/2+1\\ 21/2+1\\ 21/2+1\\ 23/2+1\\ 21/2+1\\ 23/2+1\\ 21/2+1\\ 23$	$\begin{array}{r} {}^{137}\mathrm{Cs}\\ \hline 2150\\ 2068\\ 455\\ 849\\ 1651\\ 0\\ 1575\\ 1783\\ 1273\\ 1570\\ 1916\\ 1185\\ 1671\\ 1894\\ 2784\\ 3464\\ 3464\\ \end{array}$	$\begin{array}{c} 2135\\ 2066\\ 387\\ 907\\ 1670\\ -15\\ 1576\\ 1810\\ 1320\\ 1549\\ 1916\\ 1223\\ 1642\\ 1879\\ 2827\\ 3462\\ 2827\\ 3462\\ 1822\\ 3827\\ 3462\\ 3827\\ 3462\\ 3827\\ 3462\\ 3827\\ 3462\\ 3827\\ 3462\\ 3827\\ 3462\\ 3827\\ 38$	+15 + 2 + 68 -58 -19 +15 - 1 -27 -47 +21 0 -38 +29 +15 -43 +22 -43 +22 -43 +22 -43 +22 -43 +22 -43 +22 -43 +22 -43 +22 -43 +22 -43 +22 -43 +22 +22 -43 +22 +22 +22 +22 +22 +22 +22 +22 +22 +2	$egin{array}{cccc} 0+1&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&$	¹³⁸ Ba 0 2190 2583 1436 2218 2640 2446 1899 2308 2583 2779 2415 2091 2203 3309 3184	-5 2092 2574 1485 2181 2542 2368 1913 2291 2637 2787 2046 2184 3344 3200	+5 +98 +9 -49 +37 +98 +78 -14 +17 -54 -8 +108 +45 +19 -35 -16
$\begin{array}{c} 1/2+2\\ 3/2+4\\ 5/2+1\\ 2\\ 3\\ 7/2+1\\ 2\\ 3\\ 9/2+1\\ 2\\ 3\\ 11/2+1\\ 15/2+1\\ 17/2+1\\ 21/2+1\\ 23/2+1\\ 11/2-1\\ 23/2+1\\ 11/2-1\\ 23/2+1\\ 11/2-1\\ 23/2+1\\ 11/2-1\\ 23/2+1\\ 11/2-1\\ 23/2+1\\ 11/2-1\\ 23/2+1\\ 11/2-1\\ 23/2+1\\ 11/2-1\\ 23/2+1\\ 11/2-1\\ 23/2+1\\ 11/2-1\\ 23/2+1\\ 11/2-1\\ 23/2+1\\ 11/2-1\\ 23/2+1\\ 11/2-1\\ 23/2+1\\ 11/2-1\\ 23/2+1\\ 11/2-1\\ 23/2+1\\ 11/2-1\\ 11$	$\begin{array}{r} {}^{137}\mathrm{Cs} \\ \hline 2150 \\ 2068 \\ 455 \\ 849 \\ 1651 \\ 0 \\ 1575 \\ 1783 \\ 1273 \\ 1570 \\ 1916 \\ 1185 \\ 1671 \\ 1894 \\ 2784 \\ 3464 \\ 1868 \\ 2466 \end{array}$	2135 2066 387 907 1670 -15 1576 1810 1320 1549 1916 1223 1642 1879 2827 3462 1836	$\begin{array}{r} +15 \\ +2 \\ +68 \\ -58 \\ -19 \\ +15 \\ -1 \\ -27 \\ -47 \\ +21 \\ 0 \\ -38 \\ +29 \\ +15 \\ -43 \\ +2 \\ +32 \\ +32 \end{array}$	$egin{array}{c} 0+1 & 2 & \ 1+1 & 2+1 & \ 2+1 & 2 & \ 3+1 & \ 4+1 & 2 & \ 3+1 & \ 6+1 & \ 6+1 & \ 7+1 & \ 8+1 & \ 8+1 & \ 2+1 & \ 8+$	¹³⁸ Ba 0 2190 2583 1436 2218 2640 2446 1899 2308 2583 2779 2415 2091 2203 3309 3184 3610	-5 2092 2574 1485 2181 2542 2368 1913 2291 2637 2787 2046 2184 3344 3200 3611	+5 +98 +9 +37 +98 +78 -14 +17 -54 -8 +108 +45 +19 -35 -16 -1
$\begin{array}{c} 1/2+2\\ 3/2+4\\ 5/2+1\\ 2\\ 3\\ 7/2+1\\ 2\\ 3\\ 9/2+1\\ 2\\ 3\\ 11/2+1\\ 15/2+1\\ 17/2+1\\ 21/2+1\\ 23/2+1\\ 11/2-1\\ 23/2-1\\ 1\end{array}$	$\begin{array}{r} {}^{137}\mathrm{Cs}\\ \hline 2150\\ 2068\\ 455\\ 849\\ 1651\\ 0\\ 1575\\ 1783\\ 1273\\ 1570\\ 1916\\ 1185\\ 1671\\ 1894\\ 2784\\ 3464\\ 1868\\ 3496\\ 3496\end{array}$	$\begin{array}{c} 2135\\ 2066\\ 387\\ 907\\ 1670\\ -15\\ 1576\\ 1810\\ 1320\\ 1549\\ 1916\\ 1223\\ 1642\\ 1879\\ 2827\\ 3462\\ 1836\\ 3503\\ \end{array}$	$\begin{array}{r} +15 \\ +2 \\ +68 \\ -58 \\ -19 \\ +15 \\ -1 \\ -27 \\ -47 \\ +21 \\ 0 \\ -38 \\ +29 \\ +15 \\ -43 \\ +2 \\ +32 \\ -7 \\ -7 \\ \end{array}$	$\begin{array}{c} 0+1\\ 2\\ 1+1\\ 2+1\\ 2\\ 3\\ 3+1\\ 4+1\\ 2\\ 3\\ 4\\ 5+1\\ 6+1\\ 2\\ 7+1\\ 8+1\\ 2\\ 9+2\\ 9+2\\ 1+1\\ 2\\ 9+2\\ 9+2\\ 1+1\\ 1+1\\ 2\\ 3+1\\ 3+1\\ 3+1\\ 3+1\\ 3+1\\ 3+1\\ 3+1\\ 3+1$	¹³⁸ Ba 0 2190 2583 1436 2218 2640 2446 1899 2308 2583 2779 2415 2091 2203 3309 3184 3610 4158	-5 2092 2574 1485 2181 2542 2368 1913 2291 2637 2787 2046 2184 3344 3200 3611 4108	+5 +98 +9 +37 +98 +78 -14 +17 -54 -8 +108 +45 +19 -35 -16 -1 +50
$\begin{array}{c} 1/2+2\\ 3/2+4\\ 5/2+1\\ 2\\ 3\\ 7/2+1\\ 2\\ 3\\ 9/2+1\\ 2\\ 3\\ 11/2+1\\ 15/2+1\\ 17/2+1\\ 21/2+1\\ 23/2+1\\ 11/2-1\\ 23/2-1\\ 27/2-1\\ 27/2-1\\ 127/2-$	$\begin{array}{r} {}^{137}\text{Cs}\\ \hline 2150\\ 2068\\ 455\\ 849\\ 1651\\ 0\\ 1575\\ 1783\\ 1273\\ 1570\\ 1916\\ 1185\\ 1671\\ 1894\\ 2784\\ 3464\\ 1868\\ 3496\\ 4408\\ 4408\\ \end{array}$	$\begin{array}{c} 2135\\ 2066\\ 387\\ 907\\ 1670\\ -15\\ 1576\\ 1810\\ 1320\\ 1549\\ 1916\\ 1223\\ 1642\\ 1879\\ 2827\\ 3462\\ 1836\\ 3503\\ 4424\\ -444 \end{array}$	$\begin{array}{r} +15 \\ +2 \\ +68 \\ -58 \\ -19 \\ +15 \\ -1 \\ -27 \\ -47 \\ +21 \\ 0 \\ -38 \\ +29 \\ +15 \\ -43 \\ +2 \\ +32 \\ -7 \\ -16 \\ \end{array}$	$\begin{array}{c} 0+1\\ 2\\ 1+1\\ 2+1\\ 2\\ 3\\ 3+1\\ 4+1\\ 2\\ 3\\ 4\\ 5+1\\ 6+1\\ 2\\ 7+1\\ 8+1\\ 2\\ 9+2\\ 10+1\\ \end{array}$	¹³⁸ Ba 0 2190 2583 1436 2218 2640 2446 1899 2308 2583 2779 2415 2091 2203 3309 3184 3610 4158 3622	-5 2092 2574 1485 2181 2542 2368 1913 2291 2637 2787 2046 2184 3344 3200 3611 4108 3646	+5 +98 +9 +37 +98 +78 -14 +17 -54 -8 +108 +45 +19 -35 -16 -1 +50 -24
$\begin{array}{c} 1/2+2\\ 3/2+4\\ 5/2+1\\ 2\\ 3\\ 7/2+1\\ 2\\ 3\\ 9/2+1\\ 2\\ 3\\ 11/2+1\\ 15/2+1\\ 17/2+1\\ 21/2+1\\ 23/2+1\\ 11/2-1\\ 23/2-1\\ 23/2-1\\ 27/2-1\\ 29/2-1 \end{array}$	$\begin{array}{r} {}^{137}\mathrm{Cs}\\ \hline 2150\\ 2068\\ 455\\ 849\\ 1651\\ 0\\ 1575\\ 1783\\ 1273\\ 1570\\ 1916\\ 1185\\ 1671\\ 1894\\ 2784\\ 3464\\ 1868\\ 3496\\ 4408\\ 5023\\ \end{array}$	$\begin{array}{c} 2135\\ 2066\\ 387\\ 907\\ 1670\\ -15\\ 1576\\ 1810\\ 1320\\ 1549\\ 1916\\ 1223\\ 1642\\ 1879\\ 2827\\ 3462\\ 1836\\ 3503\\ 4424\\ 5007\\ \end{array}$	$\begin{array}{r} +15 \\ +2 \\ +68 \\ -58 \\ -19 \\ +15 \\ -1 \\ -27 \\ -47 \\ +21 \\ 0 \\ -38 \\ +29 \\ +15 \\ -43 \\ +29 \\ +15 \\ -43 \\ +22 \\ -7 \\ -16 \\ +16 \end{array}$	$\begin{array}{c} 0+1\\ 2\\ 1+1\\ 2+1\\ 2\\ 3\\ 3+1\\ 4+1\\ 2\\ 3\\ 4\\ 5+1\\ 6+1\\ 2\\ 7+1\\ 8+1\\ 2\\ 9+2\\ 10+1\\ 2\\ 10+1\\ 2\end{array}$	^{138}Ba 0 2190 2583 1436 2218 2640 2446 1899 2308 2583 2779 2415 2091 2203 3309 3184 3610 4158 3622 3911	$\begin{array}{r} -5\\ 2092\\ 2574\\ 1485\\ 2181\\ 2542\\ 2368\\ 1913\\ 2291\\ 2637\\ 2787\\ 2307\\ 2046\\ 2184\\ 3344\\ 3200\\ 3611\\ 4108\\ 3646\\ 3879\\ \end{array}$	+5 +98 +9 +37 +98 +78 -14 +17 -54 -8 +108 +45 +19 -35 -16 -1 +50 -24 +32
$\begin{array}{c} 1/2+2\\ 3/2+4\\ 5/2+1\\ 2\\ 3\\ 7/2+1\\ 2\\ 3\\ 9/2+1\\ 2\\ 3\\ 11/2+1\\ 15/2+1\\ 17/2+1\\ 21/2+1\\ 23/2+1\\ 11/2-1\\ 23/2-1\\ 27/2-1\\ 29/2-1\\ 31/2-1 \end{array}$	$\begin{array}{r} {}^{137}\mathrm{Cs}\\ \hline 2150\\ 2068\\ 455\\ 849\\ 1651\\ 0\\ 1575\\ 1783\\ 1273\\ 1570\\ 1916\\ 1185\\ 1671\\ 1894\\ 2784\\ 3464\\ 1868\\ 3496\\ 4408\\ 5023\\ 5494\\ \end{array}$	$\begin{array}{c} 2135\\ 2066\\ 387\\ 907\\ 1670\\ -15\\ 1576\\ 1810\\ 1320\\ 1549\\ 1916\\ 1223\\ 1642\\ 1879\\ 2827\\ 3462\\ 1836\\ 3503\\ 4424\\ 5007\\ 5492\\ \end{array}$	$\begin{array}{r} +15 \\ +2 \\ +68 \\ -58 \\ -19 \\ +15 \\ -1 \\ -27 \\ -47 \\ +21 \\ 0 \\ -38 \\ +29 \\ +15 \\ -43 \\ +29 \\ +15 \\ -43 \\ +22 \\ -7 \\ -16 \\ +16 \\ +2 \end{array}$	$\begin{array}{c} 0+1\\ 2\\ 1+1\\ 2+1\\ 2\\ 3\\ 3+1\\ 4+1\\ 2\\ 3\\ 4\\ 5+1\\ 6+1\\ 2\\ 7+1\\ 8+1\\ 2\\ 9+2\\ 10+1\\ 2\\ 12+1\end{array}$	$^{138}Ba \\ \hline 0 \\ 2190 \\ 2583 \\ 1436 \\ 2218 \\ 2640 \\ 2446 \\ 1899 \\ 2308 \\ 2583 \\ 2779 \\ 2415 \\ 2091 \\ 2203 \\ 3309 \\ 3184 \\ 3610 \\ 4158 \\ 3622 \\ 3911 \\ 4689 \\ \hline \\ 4689 \\ \hline \\$	-5 2092 2574 1485 2181 2542 2368 1913 2291 2637 2787 2046 2184 3344 3200 3611 4108 3646 3879 4724	$\begin{array}{r} + \ 5 \\ + \ 98 \\ + \ 9 \\ - \ 49 \\ + \ 37 \\ + \ 98 \\ + \ 78 \\ - \ 14 \\ + \ 17 \\ - \ 54 \\ - \ 14 \\ + \ 17 \\ - \ 54 \\ + \ 108 \\ + \ 45 \\ + \ 19 \\ - \ 35 \\ - \ 16 \\ - \ 1 \\ + \ 50 \\ - \ 24 \\ + \ 32 \\ - \ 35 \end{array}$
$\begin{array}{c} 1/2+2\\ 3/2+4\\ 5/2+1\\ 2\\ 3\\ 7/2+1\\ 2\\ 3\\ 9/2+1\\ 2\\ 3\\ 11/2+1\\ 15/2+1\\ 17/2+1\\ 21/2+1\\ 23/2+1\\ 11/2-1\\ 23/2-1\\ 27/2-1\\ 29/2-1\\ 31/2-1 \end{array}$	$\begin{array}{r} {}^{137}\mathrm{Cs}\\ \hline 2150\\ 2068\\ 455\\ 849\\ 1651\\ 0\\ 1575\\ 1783\\ 1273\\ 1570\\ 1916\\ 1185\\ 1671\\ 1894\\ 2784\\ 3464\\ 1868\\ 3496\\ 4408\\ 5023\\ 5494\\ \end{array}$	$\begin{array}{c} 2135\\ 2066\\ 387\\ 907\\ 1670\\ -15\\ 1576\\ 1810\\ 1320\\ 1549\\ 1916\\ 1223\\ 1642\\ 1879\\ 2827\\ 3462\\ 1836\\ 3503\\ 4424\\ 5007\\ 5492\\ \end{array}$	$\begin{array}{r} +15\\ +\ 2\\ +68\\ -58\\ -19\\ +15\\ -1\\ -27\\ -47\\ +21\\ 0\\ -38\\ +29\\ +15\\ -43\\ +2\\ +32\\ -7\\ -16\\ +16\\ +2\end{array}$	$\begin{array}{c} 0+1\\ 2\\ 1+1\\ 2+1\\ 2\\ 3\\ 3+1\\ 4+1\\ 2\\ 3\\ 4\\ 5+1\\ 6+1\\ 2\\ 7+1\\ 8+1\\ 2\\ 9+2\\ 10+1\\ 2\\ 12+1\\ 8-1\end{array}$	^{138}Ba 0 2190 2583 1436 2218 2640 2446 1899 2308 2583 2779 2415 2091 2203 3309 3184 3610 4158 3622 3911 4689 3678	$\begin{array}{r} -5\\ 2092\\ 2574\\ 1485\\ 2181\\ 2542\\ 2368\\ 1913\\ 2291\\ 2637\\ 2787\\ 2307\\ 2046\\ 2184\\ 3344\\ 3200\\ 3611\\ 4108\\ 3646\\ 3879\\ 4724\\ 3631\\ \end{array}$	$\begin{array}{r} + \ 5 \\ + \ 98 \\ + \ 9 \\ - \ 49 \\ + \ 37 \\ + \ 98 \\ + \ 78 \\ - \ 14 \\ + \ 17 \\ - \ 54 \\ - \ 8 \\ + \ 108 \\ + \ 45 \\ + \ 19 \\ - \ 35 \\ - \ 16 \\ - \ 1 \\ + \ 50 \\ - \ 24 \\ + \ 32 \\ - \ 35 \\ + \ 47 \end{array}$

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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