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THE STRUCTURE OF THE LIGHTER N = 82 NUCLEI*

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Shell-model predictions for nuclei which can be characterized as 1, 2 and 3 protons outside the doubly-magic $N = 82$, $Z = 50$ core give a good accounting for recently discovered features of ^{133}Sb, ^{134}Te and ^{135}I.

Recent advances in experimental techniques have made possible the quantitative study of the lighter-mass nuclei having 82 neutrons [1-4]. Spectra have been obtained for ^{133}Sb, ^{134}Te and ^{135}I; these nuclei correspond respectively to one, two and three protons outside the $Z = 50$, $N = 82$ doubly-magic ^{132}Sn core. The properties of these systems are interesting because their presumed simplicity should permit a relatively unambiguous delineation of the various facets involved in nuclear structure phenomena. The nuclei around ^{208}Pb have been extensively studied in this same spirit in order to extract such quantities as effective charges and effective g-factors. Next to the ^{208}Pb neighborhood, the $N = 82$ region may well exhibit the best "closed shell" behavior available to us. In addition, the $N = 82$ region provides what the lead region does not, namely a long string of nuclei (14 have been studied at present) built by adding protons to the doubly-magic core. Thus for $N = 82$ we will have the opportunity to pursue the consequences of our deductions based on the simple, "few" nucleon systems through a series of "many" nucleon systems.

Actually, of course, because of the accidents of nuclear stability, the situation has been reversed in the $N = 82$ region. The naturally stable, many-proton, systems have been extensively investigated, both experimentally and theoretically, for some time, while the few-proton nuclei have just begun to be studied. In this note we present theoretical predictions for the structure of the $Z = (50+1,2,3$ and $4)$, $N = 82$ nuclei and compare these results to the presently available experimental data.

Our predictions for ^{133}Sb, ^{134}Te and ^{135}I are based on previous shell-model calculations for heavier $N = 82$ nuclei [5]. These calculations employed an MSDI residual interaction [6,7] and a model space comprised of all $0g_{7/2}$ - $1d_{5/2}$ configurations plus all configurations formed by exciting one particle from the $0g_{7/2}$ - $1d_{5/2}$ subspace to either a $2s_{1/2}$ or $1d_{3/2}$ orbit. In our initial work [5] we chose values for the SDI strength and for the single-particle-energy (SPE) splittings which optimized agreement between model and experimental excitation energies for all known positive-parity $N = 82$ states in $A = 136$ - 146 inclusive. Subsequently, because the model space is most appropriate for the lighter $N = 82$ nuclei, we readjusted the SDI strength and the SPE splittings to optimize agreement only for $A = 136$ - 140. The significant change which results from the new approach is an increase, from 0.48 MeV to 0.88 MeV, of the $0g_{7/2}$ - $1d_{5/2}$ SPE splitting. (In all of this work we have employed the shell model computer codes described by French, Halbert, McGrory and Wong [8]).

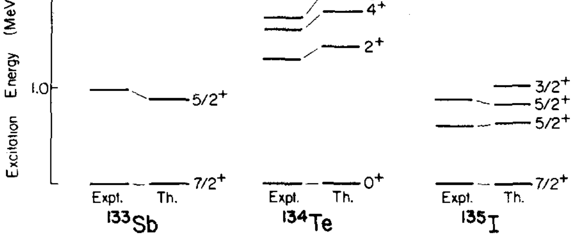

Fig. 1. Calculated and experimentally inferred spectra of the nuclei ^{133}Sb, ^{134}Te and ^{135}I.

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Table 1

Characteristics of low-lying levels of ^{133}Sb, ^{134}Te, ^{135}I and ^{136}Xe

Nucleus	J^{π}_{ν}	$E_{\text{calc.}}$	$E_{\text{expt.}}$	Model wave function (largest components)$^{a)}$
^{133}Sb	$7/2^+$	0.00	0.00	$1.00 g_7$
	$5/2^+$	0.88	0.963	$1.00 d_5$
^{134}Te	0^+_1	0.00	0.00	$0.90(g_7)^2 + 0.43(d_5)^2$
	2^+_1	1.39	1.279	$0.90(g_7)^2 + 0.26(g_7d_3) + 0.22(d_5)^2$
	4^+_1	1.76	1.576	$0.93(g_7)^2 - 0.27(g_7d_5)$
	6^+_1	1.93	1.691	$0.93(g_7)^2 - 0.37(g_7d_5)$
^{135}I	$7/2^+_1$	0.00	0.00	$0.90(g_7)^3_{J=7} - 0.42(g_7)^1 (d_5)^2_{J=0}$
	$5/2^+_1$	0.65	0.604	$0.84(g_7)^2_{J=0} (d_5)^1_{J=5} - 0.40(g_7)^3_{J=5} + 0.27(d_5)^3_{J=5}$
	$5/2^+_2$	0.82	0.871	$0.42(g_7)^2_{J=0} (d_5)^1_{J=5} + 0.80(g_7)^3_{J=5} + 0.19(d_5)^3_{J=5}$
^{136}Xe	0^+_1	0.00	0.00	$0.80(g_7)^{4,0} + 0.58(g_7)^2_{J=0}(d_5)^2_{J=0} + 0.16(d_5)^4$
	2^+_1	1.38	1.313	$0.80(g_7)^{4,2} + 0.37(g_7)^2_{J=2} (d_5)^2_{J=0} + 0.24(g_7)^2_{J=0} (d_5)^2_{J=2}$
	4^+_1	1.76	1.694	$0.82(g_7)^{4,2} + 0.38(g_7)^2_{J=4} (d_5)^2_{J=0} + 0.26(g_7)^3_{J=7} (d_5)^1_{J=5}$
	6^+_1	1.92	1.892	$0.79(g_7)^{4,2} - 0.44(g_7)^3_{J=7} (d_5)^1_{J=5} - 0.37(g_7)^2_{J=6} (d_5)^2_{J=0}$
	4^+_2	2.20		$0.81(g_7)^{4,4} + 0.24(g_7)^3_{J=7} (d_5)^1_{J=5} - 0.21(g_7)^3_{J=9} (d_3)^1_{J=3}$
	6^+_2	2.33		$0.80(g_7)^3_{J=7} (d_5)^1_{J=5} + 0.44(g_7)^{4,2} - 0.30(g_7)^1_{J=7} (d_5)^3_{J=5}$

a) Half-integral spins are given as two times their value, i.e. $7/2 = 7$. The additional quantum numbers labeling a few components are the seniorities, e.g. (g_7) [4,2] refers to the seniority 2, coupling of four 7/2 particles coupled to total angular momentum J.

We have used these $A = 136 - 140$ parameters, and the same model space assumptions, to predict the structure of the one, two and three proton systems. The calculated and experimentally observed energies are shown in fig. 1. The agreement is quite satisfactory. The dominant components of the wave functions of the low-lying states of these nuclei are listed in table 1. Similar information is also included in table 1 about states of ^{136}Xe. Several data are available on these nuclei which bear on the wave functions of these states. In table 2 we present some predictions from our wave functions for purposes of comparison to experiment.

The ^{133}Sb nucleus does not offer much material for discussion from our point of view, of course. The single gamma ray ($E_{\gamma} = 0.963$ MeV) attributed to this system [1] presumably corresponds to the "single-proton" $1d_{5/2}$ to $0g_{7/2}$ transition. Any additional energy level below the $0h_{11/2}$, $1d_{3/2}$ and $2s_{1/2}$ single-proton states at ~ 3 MeV excitation would signal the breaking of the assumed model core and problems for our approach.

In addition to the level energies of ^{134}Te, the lifetime of the 1691 keV to 1576 KeV transition has been measured [2,3] and the transition interpreted as a $J^{\pi} = 6^+$ to 4^+ electric quadrupole decay. The B(E2) extracted from the 162 nsec lifetime of this decay is $85\, e^2\mathrm{F}^4$. The calculated B(E2) for the transition between the lowest 6^+ and 4^+ states in our ^{134}Te model spectrum (under the assumptions of harmonic oscillator single-particle wave functions, $\hbar\omega = 41 A^{-1/3}$ and a proton charge of $1e$) is $39\, e^2\mathrm{F}^4$. This implies an effective charge for protons in this region of $e_{\mathrm{p}}(\mathrm{eff}) = 1.47e$. Our model wave functions for each of the lowest 0^+, 2^+, 4^+ and 6^+ states are dominated ($\sim 80\%$) by the $(g_{7/2})^2$ configuration. However, the difference between the effective proton charge derived from a pure $g_{7/2}$ assumption for these states and our present value is $1.74e$ versus $1.47e$.

The structure of the low-lying levels of ^{135}I have been studied both by gamma ray decay [1] and by proton pickup [9] from ^{136}Xe. The ^{136}Xe(d, ^{3}He) ^{135}I reaction populates the 0.604 and 0.871 MeV states with $l = 2$ transfer. Systematics argue against interpreting the higher energy state as being fed by $1d_{3/2}$ pickup, yet study of the heavier $N = 82$ nuclei also gives no evidence for any but the lowest $5/2^+$ states being populated in such pickup reactions. The experimental and calculated S-factors are presented in table 2 and it can be seen that our theory predicts this phenomenon with quantitative accuracy.

Table 2
Electromagnetic and single-nucleon transition strengths in ^{134}Te, ^{135}I and ^{136}Xe

Nucleus	$J^{\pi}_{\nu} \to J'^{\pi}_{\nu'}$	Calc.	Expt.
		B(E2)'s in units of e^2F^4	
^{134}Te	2^+_1 0^+_1	81 b)	
	4^+_1 2^+_1	81	
	6^+_1 4^+_1	39	85
^{136}Xe	2^+_1 0^+_1	122	
	4^+_1 2^+_1	9	
	4^+_2 2^+_1	65	
	6^+_1 4^+_1	1.6	0.6
	6^+_2 4^+_1	11	
		Single nucleon S-factors	
^{136}Xe $\to$ ^{135}I	0^+_1 $7/2^+_1$	318	274
	0^+_1 $5/2^+_1$	58	34
	0^+_1 $5/2^+_2$	17	12

b) e_p assumed to be 1.0e.

Its occurence depends upon the drawing close of the $[(g_{7/2})^2_{J=0}(d_{5/2})]_{J=5/2}$ state and the $[(g_{7/2})^3]_{J=5/2}$ state so that their amplitudes mix. In the BCS language we would speak of the $1d_{5/2}$ one-quasiparticle state mixing with the $0g_{7/2}$ three-quasiparticle J=5/2 state. That is, in the three proton system we witness the transition from the "superconducting" type of nuclear structure characteristic of the heavier N=82 systems to a more typical "shell-model" structure. Of course, our present shell-model treatment encompasses both types of structure simultaneously, the changes in overt behavior just arising from the different numbers of active particles.

Although ^{136}Xe, the 4-proton system, is a stable isotope, rather little is experimentally known about the structure of its low-lying states. One feature that has been recently discovered [4] is an isomeric gamma ray transition that appears to be a 6^+ to 4^+ E(2) transition analogous to that discussed for ^{134}Te. The strength of this transition in ^{136}Xe is 0.6 e^2F^4, as opposed to the value of 85 e^2F^4 in ^{134}Te. Our predicted B(E2) using the effective proton charge of 1.47e, is 3.5 e^2F^4. This marked reduction in strength in going from the 2 proton to the 4 proton system can be understood as the action of a selection rule [10] which forbids transitions between wave function components characterized by a half-full orbit and the same seniority. Heyde et al. [11] have noted the same feature in their BCS wave functions for ^{136}Xe.

We conclude with the following comments. 1) The good agreement between the newly available data on the light N=82 isotones and our predictions for these systems as extrapolated from our calculations for the heavier nuclei of the chain seems to complete the validation of this sort of theoretical approach to the N=82 region. 2) The existence of model wave functions of good predictive value justifies further intensive experimental study of the light N=82 nuclei aimed at measuring quantities which, when interpreted with the aid of these wave functions, can yield information about effective single-particle operators. 3) Experimental information presently available about the effective charge for E2 transitions in this region is consistent with the value e_p(eff) $\sim$ 1.5e, which is in turn consistent with results presently available from analysis of data in the lead region [12] and with the results of detailed shell model studies [13] of nuclei in the mass 20-40 region.

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