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TRANSITION PROBABILITIES AND STATIC MOMENTS IN TRANSITIONAL NUCLEI

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1. Introduction

Electromagnetic transition probabilities and static moments of excited nuclear states are known to be good probes of nuclear structure. Therefore, a systematic analysis of the large amount of existing experimental data for these observables is expected to provide valuable information about the respective isotopes. It is the purpose of this talk to show that a combined analysis of static magnetic moments of 2_1^+ states and $B(E2)$ transition probabilities for even-even nuclei can be used to obtain effective numbers of valence nucleons. This kind of information is of particular interest in cases where subshell closures are found. For example, it is well known¹ that for the transitional nuclei in the $A=150$ region the $Z=64$ subshell is active when the number of neutrons $N < 90$, but disappears for $N \geq 90$. A similar situation exists in the $A=100$ region, where the $Z=38$ subshell is active for $N \leq 58$.

In the following sections we present the method by which effective numbers of valence protons and neutrons can be deduced from $B(E2)$ and g -factor data, and show applications of this method to the $A=150$ and $A=100$ transitional regions. Part of these results were recently published².

2. Transition probabilities and magnetic moments in IBA-2.

In order to make a systematic analysis of experimental data for some observable, we need a theoretical model to guide us. In the present case, we use the proton-neutron version of the interacting boson model (IBA-2). There are two main reasons for this. Firstly, we are mainly interested here in properties of even-even collective nuclei and this model is known to provide a good description of these nuclei. Secondly, in IBA-2 we have simple analytical formulas for the $B(E2)$ transition probabilities and the g -factors of 2_1^+ states. For the latter quantity, it was shown³ that the following linear relation exists:

$$g(2_1^+) = (g_\pi N_\pi + g_\nu N_\nu) / N_t \quad (1)$$

where N_π (N_ν) are the numbers of proton (neutron) bosons, $N_t = N_\pi + N_\nu$, and g_π (g_ν)

the g-factors of the single bosons. Equation (1) was derived³ using only the assumption that F spin is a good quantum number, and is therefore approximately valid for the 2_1^+ states of most even-even nuclei.

For the B(E2) transition probabilities the situation is more complex. There is no single universal B(E2) analytical formula valid for all even-even nuclei. However, simple relations exist for the three dynamical symmetries of the U(6) group⁴, namely, U(5), SU(3) and O(6):

$$B(E2: 0_1^+ \rightarrow 2_1^+) = 5/N (e_\pi N_\pi + e_\nu N_\nu)^2 \quad [U(5)] \quad (2)$$

$$= (2N+3)/N (e_\pi N_\pi + e_\nu N_\nu)^2 \quad [SU(3)] \quad (3)$$

$$= (N+4)/N (e_\pi N_\pi + e_\nu N_\nu)^2 \quad [O(6)] \quad (4)$$

Recently, it was shown⁵ that for a large number of nuclei throughout the O(6)-SU(3) region a simple approximate analytic expression can be used:

$$B(E2: 0_1^+ \rightarrow 2_1^+) = 0.05(1 - 0.1\chi)^2(1 + 1/N_t)^2(e_\pi N_\pi + e_\nu N_\nu)^2 \quad (5)$$

where χ is the parameter of the quadrupole operator.

The method we propose to determine effective numbers of valence particles is basically to use experimental $g(2_1^+)$ and B(E2) values for a specific isotope, and then extract N_π^{eff} , N_ν^{eff} from equation (1) and the appropriate B(E2) expression (i.e., one of eqs. (2)-(5)) by solving two equations with two unknowns. In this approach we need to know the values of the effective g-factors (g_π, g_ν) and the effective charges (e_π, e_ν) of the (proton, neutron) bosons. These parameters can be deduced by a systematic analysis of $g(2_1^+)$ and B(E2) data in collective nuclei where we assume that we know the values of N_π , N_ν . We present this analysis in the next section.

3. Effective charges and boson g-factors in collective nuclei.

Equation (1) is a linear relationship between $g(2_1^+)$ and N_π, N_ν . g_π, g_ν can be deduced as the slope and intercept from a linear fit of gN_t/N_ν vs. N_π/N_ν . This was done⁶ for 65 nuclei in the range A=70-200. The nuclei were divided into six groups. The resulting g_π, g_ν for these groups are plotted in Fig 1 against the average mass number A of each group. We see that in general, g_π tends to increase while g_ν decreases with increasing A. The sum $g_\pi + g_\nu$ stays constant at about 0.7 in all cases. A notable exception from the smooth dependence of g_π, g_ν with A occurs at A=170. These are the Er, Yb isotopes, and the reasons for their anomalous behaviour were discussed elsewhere^{6,7}.

The extraction of boson effective charges from experimental B(E2) data is more complicated and has to be done by using the appropriate equation among eqs. (2)-(5). Sala et al.⁸ have used this approach and obtained e_π, e_ν for 36 nuclei in the Dy-Os region. They obtained : $e_\pi = 0.15eb$, $e_\nu = 0.11eb$. However, they also observed considerable variations of B(E2) values with Z,A which could not be explained by using constant values of the effective charges. In our analysis we need the effective charges in the A=100 and A=150 regions for vibrational and for deformed nuclei. To obtain these values, we made linear fits of $T = k(N_\pi, N_\nu)B(E2)^{1/2}$ vs. N_π/N_ν . The nuclei were classified according to Z and/or A, and structure (i.e., vibrational, rotational). The function $k(N_\pi, N_\nu)$ is obtained from eqs. (2)-(5) after simple algebraic manipulations. We have different $k(N_\pi, N_\nu)$ functions for the different symmetries. The experimental B(E2) values were taken from the compila-

Figure 1 Systematics of g_π, g_ν

tion of Raman et al.⁹ As an example, in fig 2 we present the linear fits for the ⁹⁶⁻¹⁰²Ru isotopes, and for six neutron-rich Ba, Ce, Gd isotopes (groups 2,6 in Table 1). The latter are known to be deformed nuclei and eq (5) was used with $\chi = -0.52$. A variation of χ of 20% has a negligible effect on the results of the calculation.

The various groups of nuclei for which we extracted effective charges are listed in Table 1. For purposes of comparison, we included the results for heavier nuclei, in the A = 160-190 range. From the table we see that for all deformed nuclei (SU(3), O(6)) the ratio e_ν/e_π is of the order of 0.3-0.6, in agreement with the recent work of Raman et al.⁹ For the vibrational (U(5)) nuclei this ratio is considerably larger than 1.00. The fact that neutrons have a larger effective charge than protons was first mentioned by Hamilton et al.¹⁰ for vibrational nuclei in the A=140 region (group 5 in Table 1). Here we report this effect for vibrational nuclei in the A=100 region (groups 1,2). The reason for this effect is at present unclear. It was suggested¹⁰ that it may be related to the different shells occupied by the protons and neutrons, and to the fact that the given values have a (length)² factor incorporated in them.

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4. Effective numbers of valence nucleons.

We will use now the effective g-factors and charges determined in the previous sections, equations (1)-(5), and experimental $B(E2)$ and $g(2_1^+)$ data to determine the effective numbers of valence protons, neutrons (N_p^{eff} , N_n^{eff}) for transitional nuclei in the $A=150$ and $A=100$ regions. In order to be consistent we will follow this procedure only for nuclei which were not included in the linear fits described in the previous section. The results for the $A=150$ region are given in fig 3. The dissipation of the $Z=64$ subshell when N increases between $84 \leq N \leq 92$ is clearly seen for the Sm, Nd, and Ce isotopes. The Ba isotopes do not show this effect because Ba is below midshell for both the

Table 1 Effective boson charges for groups of isotopes in the range $A=90-200$

Group No.	Isotopes	e_π (eb)	e_ν (eb)	e_ν/e_π	Eq. used for fit
1	94-96 _{Mo}	0.080	0.121	1.51	(2)
2	96-102 _{Ru}	0.095	0.166	1.75	(2)
3	100 _{Sr} , 102 _{Zr} , 106 _{Mo}	0.194	0.125	0.64	(3)
4	108-112 _{Ru}	0.159	0.055	0.35	(4)
5	138 _{Ba} -146 _{Nd} ^a	0.12	0.24	2.00	(2)
6	146 _{Ba} -160 _{Gd}	0.169	0.095	0.56	(5)
7	156-164 _{Dy}	0.173	0.064	0.37	(5)
8	180-186 _W	0.234	0.073	0.31	(5)
9	182-192 _{Os}	0.221	0.083	0.38	(5)

a) From Ref. 10.

Figure 2 Fits of T vs. N_π/N_ν for vibrational Ru isotopes and deformed neutron-rich Ba, Ce, Gd isotopes.

50-64 and 50-82 shells. It is also remarkable that the deduced numbers of valence neutrons behave as expected from normal counting (solid lines).

In the A=100 region the situation is not as clear. The main problem is the lack of sufficient experimental data, especially magnetic moments. Another difficulty arises because in this region it is not always possible to use analytical formulas which are valid only for the limiting symmetries of IBA. A possible way to circumvent this problem is to perform full numerical calculations. In the following we will make a first estimate of the effective number of valence particles without using the numerical code. We first consider the ^{84}Kr , ^{86}Sr isotopes. We assume we can use here the U(5) equation for the B(E2) transition probabilities.

Figure 3 N_p^{eff} , N_n^{eff} around A=150

This assumption is not unreasonable in view of the level structure of these isotopes. We want now to test the hypothesis that for these nuclei the Z=38 subshell is active. Since there is no available data for magnetic moments of 2_1^+ states in this case, we will assume that the numbers of neutrons are those from normal counting. Under this assumption, we can determine the effective numbers of protons from the known experimental B(E2) values. For the effective charges e_π, e_ν we use averages of the respective values of groups 1,2 in Table 1. The resulting numbers of valence protons are given in Table 2. We see that the N_p^{eff} values are much smaller than those from normal counting in the 28-50shell. We therefore have here direct evidence that a subshell is present, similar to what we have found in the A=150 region.

Table 2 N_p^{eff} in Kr, Sr, Zr, Mo isotopes.

Isotope	N_p (normal counting)	N_p^{eff}
^{84}Kr	8	1.8
^{86}Sr	10	0.5
^{98}Sr	10	4.6
^{100}Zr	10	0.0
^{102}Mo	8	8.5

Additional evidence is provided by $g(2_1^+)$ data for ^{98}Sr , ^{100}Zr , ^{102}Mo .¹¹⁻¹³ Although $B(E2)$ values do exist for these nuclei, we can not use them in the simple way described above because the analytical relations are not valid. Again, in order to obtain a first estimate without using the numerical code we assume that the valence neutrons behave "normally", and calculate N_p^{eff} using eq 1 and g_π, g_ν from the systematics ($g_\pi=0.48$, $g_\nu=0.33$). The resulting N_p^{eff} are also given in Table 2. We see that while for ^{100}Zr and ^{98}Sr the $Z=38$ subshell is still active, for ^{102}Mo it is not.

In conclusion, we have shown that a systematic analysis of $B(E2)$ and $g(2_1^+)$ data can provide direct evidence for the existence of subshell closures. We should emphasize that at this point the evidence in the $A=100$ region is not as conclusive as in the $A=150$ region, and more experimental data and theoretical calculations (like, e.g., full numerical IBA computations) are needed to further substantiate the results presented in this work.

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