Revista Brasileira de Física, Vol. 20, nº 4, 1990

Width of M1 states in even Ca isotopes

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Received October 11, 1990

Abstract We estimate the spreading width of M1 states in Ca isotopes for the purpose of trying to understand the missing strength specially in ^{44}Ca. We do this by means of a doorway calculation, where states explicitly considered have a level of complexity next to the independent-particle M1 state.

1. Introduction

The density of nuclear levels increases rapidly with the increasing excitation energy, due to the greater number of nucleons that can participate in excitations. Therefore, even if we have a weak coupling of the motion of the individual nucleon with the excitation modes involving many nucleons, this will be enough to produce strong mixing of nearest configurations. The nuclear stationary states then get a more complex structure and any such state may contain only a small amplitude of the simpler wave function.

We can characterize the fragmentation of a given excitation mode involving simple configurations by its strength function. The simplest characterization of the strength functions is in terms of its mean energy and spreading width $\Gamma^{\downarrow}$, due to mixing with more complex configurations. This width is to be distinguished from the escape width $\Gamma^{\uparrow}$, which is associated with the decay lifetime by particle emission.

The mean energy can be calculated by means of one-body mean-field theory (Hartree-Fock), but its spreading width can only be calculated if we introduce couplings of the simple mode with more complex configurations. We will compute the mixing of the simple mode with excitations at the next level of complexity in the sense of the independent particle model. These states, henceforward called doorways, may in turn mix with still more complicated states. However, this further mixing should not affect the aforementioned properties of the strength function for the simple modes, that is, it should change neither the mean energy of the distribution nor its spreading width[1,2].

It is well known that there is a systematic quenching factor of the M1 (Magnetic dipole) and Gamow-Teller (G.T.) sum rules[3] if one assumes that all the available strength is exhausted in the vicinity of the mean energies of the respective collective modes. There are theories[4] that associated the G.T. quenching to mixing of Δ-hole states with the nucleon-hole ones, while other theories[5] suggest that the observed G.T. quenching arises from spreading effects due to coupling to two particle-two hole states. In the present paper we will limit ourselves to discuss an apparent anomaly of the M1 strength that occurs in even Ca isotopes. Fig. (1)[6] shows identified M1 levels in even Ca isotopes. Especially striking is the case of the ^{44}Ca isotope where is no detected M1 intensity in the excitation energy region around 10 Mev, unlike what is found for ^{42}Ca and ^{48}Ca.

In what follows we estimate the spreading width of the strength function of the M1 mode of even Ca isotopes. It will be shown that the presence of a special doorway in ^{44}Ca considerably increases the estimated spreading width in this case. This leads to the suggestions that the M1 strength could be much more fragmented, and therefore harder to detect, in this nucleus.

2. An overview of the theoretical model for the spreading width calculation

The state that dominantes the M1 excitations of the ground state of Ca isotopes (described as $|d(7/2)^n O^+>)$ is the spin-flip state $f_{7/2} \rightarrow f_{5/2}$, which we will designate as $|D>$ (see fig. 2).

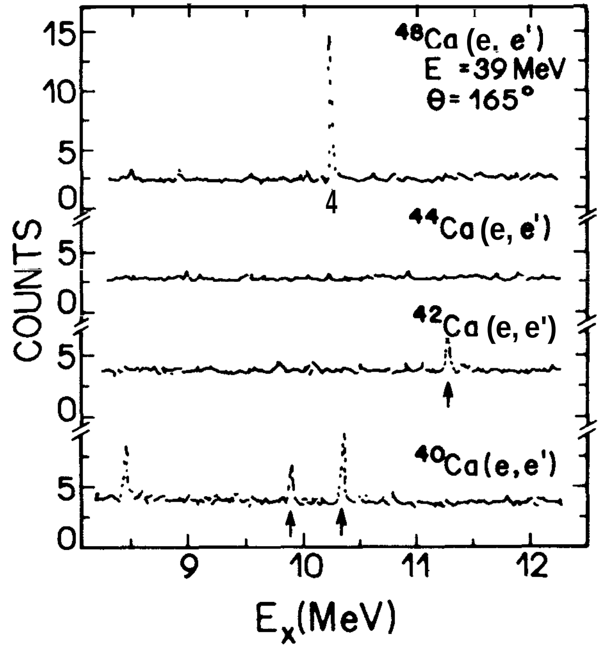

Fig. 1 - M1 transitions detected by Darmstadt in Ca isotopes[6] Arrows indicate levels identified as M1.

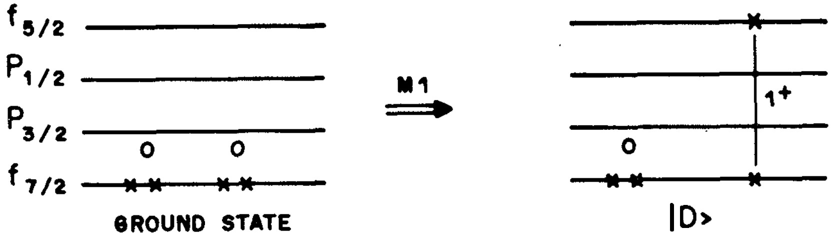

Fig. 2 - M1 excitations in ^{44}Ca.

The ^{40}Ca core is assumed inert. This is clearly an approximation since ^{40}Ca itself shows M1 excitations, see fig. 1. However, for the purpose of comparing the several Ca isotopes, we assume that the correlations that might account for the observed M1 strength in ^{40}Ca vary smoothly as the $f_{7/2}$ shell is filled. They should therefore play no relevant role in the special features found in ^{44}Ca.

It is possible to expand the state $|D>$ into nuclear eigenstates $|i>$ [7]

$$|D>=\sum_i |i><|D>=\sum_i d_i|i> \quad ; \quad H|i>=E_i|i>$$

since the states $|i>$ form a complete set. The problem to obtain the fragmentation of the state $|D>$ into several states $|i>$, is that of obtaining the distribution of weights $|d_i|^2$. The resolvent function

$$R_D(z)=<D|\frac{1}{z-H}|D>=\sum_i \frac{|d_i|^2}{z-E_i}$$

contains all the information about the fragmentation. It has simple poles at the energies E_i wth residues $|d_i|^2$.

Now, we define the projectors

$$\hat{D}\equiv|D><D|$$

and

$$\hat{Q}\equiv 1-\hat{D}$$

so that

$$\begin{aligned} H|D>&=H_{QD}|D>+H_{DD}|D>=H_{QD}|D>+|D><D|H|D>= \\ &=H_{QD}|D>+\bar{E}_D|D> \end{aligned}$$

and then we can see that the state $|D>$ is not an eigenstate of H when there is a coupling between $|D>$ and its orthogonal subspace. Making use of the operator identity

$$\hat{D}\frac{1}{z-H}\hat{D}=\hat{D}\frac{1}{z-H_{DD}-H_{DQ}\frac{1}{z-H_{QQ}}}\hat{D}$$

we may show the effects of H_{QD}, explicitly in the resolvent function

$$R_D(z)=\frac{1}{z-\bar{E}_D<D|H\hat{Q}\frac{1}{z-H_{QQ}}\hat{Q}H|D>}$$

When $H_{QD} \neq 0$, the state $|D>$ is not an eigenstate of H and the poles of $R_D(Z)$, that are the energies E, of the stationary states $|i>$, will be the solutions of the dispersion equation

$$E_i - \bar{E}_d = \sum_q \frac{|<D|H|q>|^2}{E_i - E_q}$$

where

$$H_{QQ}|q>= E_q|q> \quad , \quad <q|q'>= \delta_{qq} \quad ,$$

and

$$\hat{Q} = \sum_q |q><q|$$

The desired mean properties of the strength function can readily be obtained by evaluating the resolvent function at complex energy E $+ iI$. This amounts essentially to taking an energy average of $R_D(Z)$ with a Lorentzian weight function

$$W(E - E') = \frac{1}{\pi} \frac{I}{(E - E')^2 + I^2}$$

The result is

$$R_D(E + iI) = \frac{1}{E + iI - \bar{E}_D - \Delta_D + \frac{1}{2}\Gamma_D^{\downarrow}}$$

where the energy shift Δ_D is

$$\Delta_D = \sum_q \frac{(E - E_q)|<D|H|q>|^2}{(E - E_q)^2 + I^2}$$

and

$$\Gamma^{\downarrow} = 2\sum_q \frac{I|<D|H|q>|^2}{(E - E_q)^2 + I^2} \cong 2\pi\rho_q\overline{|<D|H|q>|^2}$$

This form is appropriate in situations involving a dense spectrum of background states $|q>$, in the sense that one may choose I large as compared to the mean level spacing but still small as compared to the spreading width $\Gamma^{\downarrow}$. The averaged resolvent function displays now a complex pole that characterizes the position and the spreading of the strength distribution associated with the mode $|D>$. The essential observation for estimating $\Gamma^{\downarrow}$ is that one does not need in fact to use the actual complicated background states $|q>$. Actually, only those

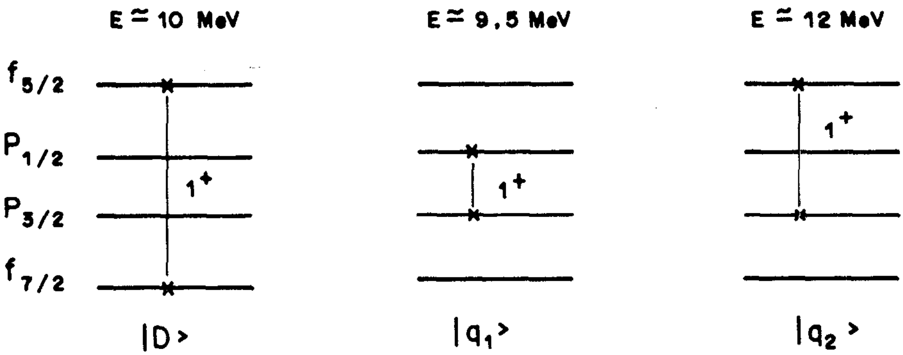

Fig. 3 - $|D>$ and doorways states in ^{42}Ca.

components of the $|q>$ which are simple enough to couple to $|D>$ via H (which contains at most two-body operators) will be relevant. Therefore, we estimate $\Gamma^{\downarrow}$ by taking an inventory of the doorway states of relevant complexity in the Q subspace, and use them, together with the corresponding level density, in the above expression for $\Gamma^{\downarrow}$. The validity of this procedure can be maintained to the extent that the strength of the doorways is itself not strongly displaced by spreading effects in the next level of complexity.

The point that must be emphasized is that this method for obtaining the spreading width does not ignore the possible effects of other more complex configurations, although they are not dealt with explicitly. In fact, the degree of fragrnentation is described only in terms of average parameters which are essentially determined at the doorway level via the distribution of coupling strength.

3. Calculations and results

We will estimate the width $\Gamma^{\downarrow}$ of the ^{42}Ca and ^{44}Ca isotopes, treating ^{40}Ca as a hard core. We will consider as relevant doorways all the 1^+ states in the $p-f$ shell with energies near 10 Mev, having nonzero coupling to the M1 state $|D>$. Experimental single-particle energies were used.

In the case of ^{42}Ca, we have the situation shown in fig. (3).

Width of M1 states in euen Ca isotopes

Using the realistic two-body interaction for this mass region derived by Kuo and Brown[8], we obtain

$$< D|H|q_1 > \simeq 80 \text{ Kev}$$

$$< D|H|q_2 > \simeq 35 \text{ Kev}$$

which yields

$$\Gamma^{\downarrow} \simeq 10 \text{ Kev}$$

In the case of ^{44}Ca, we have the situation shown in fig. (4).

$$E \simeq 10 \text{ Mev}$$

Using the Kuo and Brown interaction, we can evaluate the matrix elements $< D|H|q_i >$, with the result

$< D\|H\|q_1 > \simeq 70$ Kev	$< D\|H\|q_6 > \simeq 10$ Kev
$< D\|H\|q_2 > \simeq 40$ Kev	$< D\|H\|q_7 > \simeq 90$ Kev
$< D\|H\|q_3 > \simeq 90$ Kev	$< D\|H\|q_8 > \simeq 150$ Kev
$< D\|H\|q_4 > \simeq 1.9$ Kev	$< D\|H\|q_9 > \simeq 20$ Kev
$< D\|H\|q_5 > \simeq 10$ Kev	$< D\|H\|q_{10} > \simeq 10$ Kev

The spreading comes out in this case as

$$\Gamma^{\downarrow} \simeq 1 \text{ Mev}$$

The most important contribution to this value comes from $|q_4 >$. We can see that the spreading width of ^{44}Ca is about 100 times that of ^{42}Ca. This ratio is perhaps more significant than the values of the spreading widths themselves, which depend on the specific interaction used and may be more sensitive to the fact that we did not take the ^{40}Ca correlations into account.

The spreading widths for ^{48}Ca and ^{46}Ca can be related to those of ^{42}Ca and ^{44}Ca respectively by using particle-hole conjugation. One should therefore expect a spreading width for ^{46}Ca which is also about 100 times larger than that of ^{48}Ca.

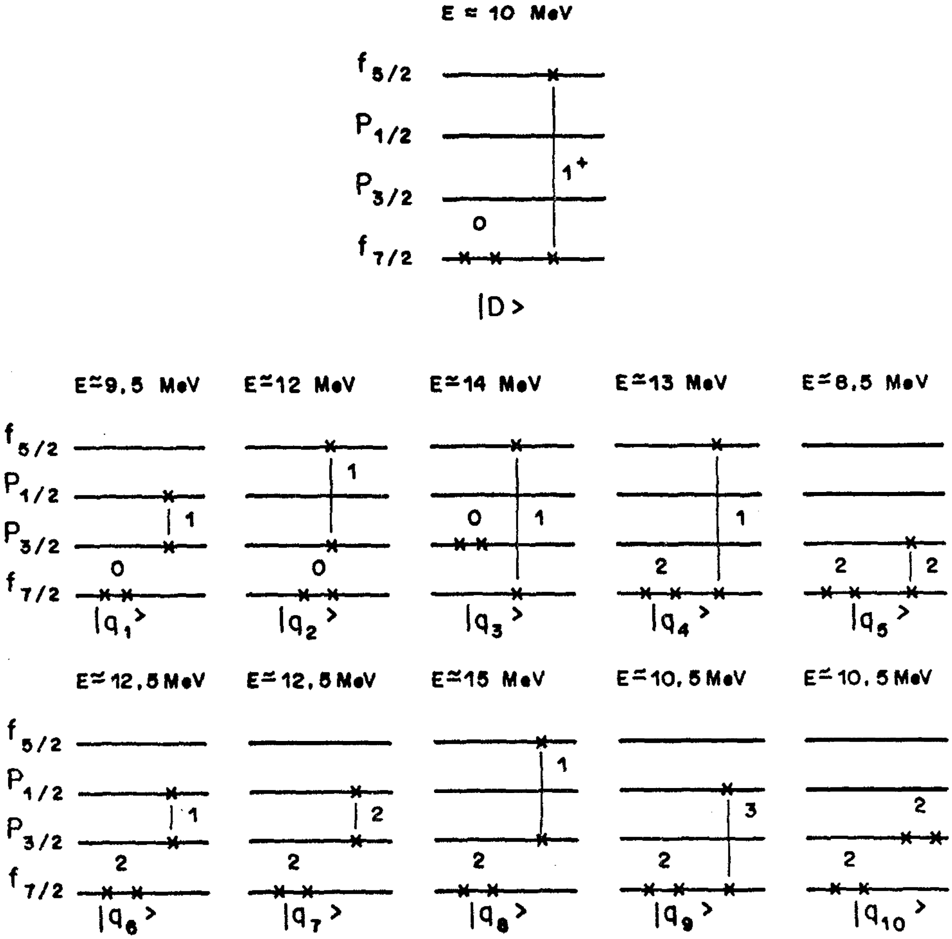

Fig. 4 - $|D>$ and doorways states in ^{44}Ca.

4. Conclusions

The above estimates of the spreading widths for the M1 states in the even Ca isotopes indicate values for ^{44}Ca and ^{46}Ca which are two orders of magnitude larger than for the remaining isotopes. This suggests that the M1 strength is, in these nuclei, much more fragmented than in the other isotopes, and favors the interpretation of **fig.** 1 in terms of the ensuing difficulty in identifying M1 transitions experimentally in ^{44}Ca.

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Resumo

Estimamos a largura da transição **M1** nos isótopos do Ca com o objetivo de tentar explicar as atenuações das intensidades observadas, especialmente no ^{44}Ca. Fizemos isso através de um cálculo com ***doorways*** onde são considerados os níveis mais próximos de complexidade ao estado de partícula independente responsável pela transição M1.