In celebrating Iachello’s 60th birthday we underline many seminal contributions for the study of the degrees of freedom relevant for the structure of nuclei and other hadrons. A dipole degree of freedom, well described by the spectrum generating algebra U(4) and the Vibron Model, is a most natural concept in molecular physics. It has been suggested by Iachello with much debate, to be most important for understanding the low lying structure of nuclei and other hadrons. After its first observation in $^{16}$O it was also shown to be relevant for the structure of heavy nuclei (e.g. $^{218}$Ra). Much like the Ar-benzene molecule, it is shown that molecular configurations are important near threshold as exhibited by states with a large halo and strong electric dipole transitions. The cluster-molecular Sum Rule derived by Alhassid, Gai and Bertsch (AGB) is shown to be a very useful model independent tool for examining such dipole molecular structure near threshold. Accordingly, the dipole strength observed in the halo nuclei such as $^6$He, $^{11}$Li, $^{11}$Be, $^{17}$O, as well as the N=82 isotones is concentrated around threshold and it exhausts a large fraction (close to 100%) of the AGB sum rule, but a small fraction (a few percent) of the TRK sum rule. This is suggested as an evidence for a new soft dipole Vibron like oscillations in nuclei.

1 Molecular Dipole Symmetry

A molecular degree of freedom is characterized by excitations that involves the relative motion of two tightly bound constituents and not the excitation of the objects themself. Hence it is associated with a polarization vector known as the separation vector. Such a vector can be classically described in a geometrical model in three dimensions or by using the corresponding group U(4) and the very succesful Vibron model of molecular Physics. This model has two symmetry limits that correspond to the geometrical description of Rigid Molecules, the O(4) limit, or Soft Molecules, the U(3) limit.

A most comprehensive discussion of such molecular structure and the Vibron model can be found in Iachello-Levine book on "Algebraic Thoery of Molecules". In Fig. 1 taken from that book we show the characteristic dimensions of the Ar-benzene molecule. The argon atom is losely bound to the (tightly bound) benzen molecule by a van der Waalls polarization and thus this molecular state lies close to the dissociation limit. We note that the relative dimension and indeed the very polarization phenomena are reminscent of a halo structure where the argon atom creates a "halo" around the benzen molecule.

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Work Supported by USDOE Grant No. DE-FG02-94ER40870.
2 The AGB Cluster Sum Rule

The polarization phenomena associated with a molecular state implies that it should be associated with dipole excitations of the separation vector. In this case expectation values of the dipole operator do not vanish as the center of mass and center of charge of the polarized molecular state do not coincide. Hence molecular states give rise to low lying dipole excitations. While the high lying Giant Dipole Resonance (GDR) is associated with a Goldhaber-Teller excitation of the entire neutron distribution against the proton distribution, a molecular excitation involves a smaller fraction of the nucleus at the surface and is expected to occur at lower excitation than the GDR; i.e. a soft dipole mode.

The GDR exhausts the Thomas-Reiche-Kuhn (TRK) Energy Weighted Dipole Sum Rule as applied to nuclei:

\[ S_1(E_1; A) = \sum_i B(E_1; 0^+ \rightarrow 1^-_i) \times E^*(1^-_i) \]

\[ = \frac{9}{4\pi} \alpha Z N^2 A \times \frac{e^2 h^2}{2m} \]  

(equ. 1)

And for a molecular state Alhassid, Gai and Bertsch derived sum rules by subtracting the individual sum rules of the constituents from the total sum rule:

\[ S_1(E_1; A_1 + A_2) = S_1(A) - S_1(A_1) - S_1(A_2) \]

\[ = \frac{9}{4\pi} \frac{Z_2 A_2}{AA_1 A_2} \times \frac{e^2 h^2}{2m} \]  

(equ. 2)

\[ S_1(E_1; \alpha + A_2) = \frac{9}{4\pi} \frac{(N-Z)^2}{AA(A-4)} \times \frac{e^2 h^2}{2m} \]  

(equ. 3)

\[ S_1(E_1; n + A_2) = \frac{9}{4\pi} \frac{Z^2}{AA(A-1)} \times \frac{e^2 h^2}{2m} \]  

(equ. 4)

\[ S_1(E_1; 2n + A_2) = \frac{9}{4\pi} \frac{2Z^2}{AA(A-2)} \times \frac{e^2 h^2}{2m} \]  

(equ. 5)
The molecular sum rule, equ (2), was shown to be useful in elucidating molecular (cluster) states in $^{18}O$ where the measured B(E1)'s and B(E2)'s exhaust 13% and 23%, respectively, of the molecular sum rule$^{10}$. Similarly, these molecular states in $^{18}O$ have alpha widths that exhaust 20% of the Wigner sum rule. The branching ratios for electromagnetic decays in $^{18}O$ were also shown to be consistent with predictions of the Vibron model in the U(3) limit$^{11}$. Indeed the manifestation of a molecular structure in $^{18}O$ has altered our understanding of the coexistence of degrees of freedoms in $^{18}O$$^{12}$. Similar observations were also made in the heavy nucleus $^{218}Rao^{13}$.

Fig. 2: Dipole strength measured in $^{11}Li$$^{14}$.

Fig. 3: Dipole strength measured in N=82 isotones$^{20}$.

The dipole strength at approximately 1.2 MeV in $^{11}Li$$^{14}$, shown in Fig. 2, exhausts approximately 20% of the molecular sum rule, and the total strength integrated up to 5 MeV exhausts approximately 100% of the cluster sum rule$^{15,16}$, but it only exhausts approximately 8% of the TRK sum rule, see table 1. We
emphasize that the experimental efficiency at for example 6 MeV is very large (30%), but no strength is found at higher energies beyond 100% of the molecular sum rule. These two facts strongly suggest the existence of a low lying soft dipole mode in $^{11}$Li. Similar observation are reported in $^{11}$Be, oxygen isotopes $^{18}$O and $^6$He, believed to exhibit a halo structure. The N=82 isotopes also show a dipole strength near threshold as shown in Fig 3. These results are summarized in Table 1.

The ratio of the TRK/AGB sum rules is given by:

$$TRK/AGB = \frac{NZ_{A_1}A_2}{(Z_{A_1} - Z_{A_2})^2}$$

\[ (\alpha) = \frac{(N - Z)^2}{NZ(A - 4)} \]

\[ (1n) = \frac{N(A-1)}{Z} \]

\[ (2n) = \frac{N(A-2)}{2Z} \]

Table 1: Measured E1 strength in nuclei.

| Nucleus | $<E^*>$ | TRK     | TRK/AGB  | AGB      |
|---------|---------|---------|----------|----------|
| $^{11}$Li $^{14,15}$ | 1.2 MeV | 8.0 ± 2.0% | (2n) 12 | 96 ± 24% |
| $^{11}$Be $^{17}$ | 1.0 MeV | 5.0% | (1n) 18 | 90% |
| $^{17}$O $^{18}$ | < 15 MeV | 4% | (1n) 18 | 72% |
| $^{138}$Ba $^{20}$ | 6.5 MeV | 0.78 ± 0.15% | (1n) 200 | 156 ± 30% |

3 Conclusions

In conclusions we demonstrate that molecular configurations play a major role in the structure of light and heavy nuclei. Unlike the Giant Dipole Resonance that involves oscillation of the entire neutron-proton distributions, these Vibron states involve only oscillations of the surface of the nucleus, and hence they lie at lower energies than the GDR. Similarly, while the GDR exhausts the TRK sum rule, the Vibron states exhausts the AGB cluster sum rule.

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