Electric Dipole States and Time Reversal Violation in Nuclei.

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Abstract: The nuclear Schiff moment is essential in the mechanism that induces a parity and time reversal violation in the atom. In this presentation we explore theoretically the properties and systematics of the isoscalar dipole in nuclei with the emphasis on the low-energy strength and the inverse energy weighted sum which determines the Schiff moment. We also study the influence of the isovector dipole strength distribution on the Schiff moment. The influence of a large neutron excess in nuclei is examined. The centroid energies of the isoscalar giant resonance (ISGDR) and the overtone of the isovector giant dipole resonance (OIVGDR) are given for a range of nuclei.

1. Introduction

There is a close connection between collective nuclear motion and symmetries in the nuclear Hamiltonian. In some instances collective excitations are the result of the existence of certain symmetries in the system. One of the best examples is the isobaric analog resonance that results from the charge symmetry of the nuclear force. In other instances however collective excitations, such as giant resonances, serve as intermediate states in the process of breaking symmetries. In this paper we will discuss the role the isoscalar and isovector dipole strength in determining the amount of time reversal violation in spherical nuclei. In particular the contribution of low-lying dipole strength will be examined.

The study of giant resonances is not new in nuclear physics. However there is a continuous research of this subject as new resonances are found and new properties of the resonances are discovered. Moreover it is now clear that many of the resonances play an important role in determining properties of nuclear structure and reactions and contribute to the understanding of nuclear phenomena. For example, a whole class of isovector giant resonances helps in the study of the symmetry energy, the determination of isospin mixing, etc. In a recent paper [1] it was pointed out that the isoscalar dipole (ISD) resonance [2, 3] could have a sizeable contribution to the nuclear Schiff moment [4] whose operator is the same as the operator commonly used in the study of the ISD strength distribution. In recent years new resonances were studied at relatively low excitation energies. Concentrations of low-lying isovector dipole strength was observed in many nuclei throughout the periodic table. These enhancements were termed as isovector pygmy dipole resonances (PDRs). Also in the case of the isoscalar dipole, low-lying strength was observed [3].

2. The isoscalar dipole and the Schiff moment

The operator for the ISD is:

\[ D = \sum_i (r_i^3 - \frac{5}{3} \langle r_i^2 \rangle) r_i \]  

(1)

The existence of a static dipole moment in an atom means that the time reversal symmetry (as well as parity) are not conserved. Measurements of a static dipole in a neutral atom will indicate that these symmetries are broken. However, since the mean value of the nuclear dipole moment is screened by the electrons in the atom, the atomic electric dipole moment is generated by the nuclear Schiff moment [4]. This moment exists because of the finite size of the nucleus. Apart from a normalization constant the Schiff operator is identical to the isoscalar dipole moment.
\begin{equation}
S = \frac{1}{10} \sum_{i} (r_i^2 - \frac{5}{3} < r^2 > r_i \tag{2}
\end{equation}

In the neighboring odd-even nucleus with one nucleon in orbit \( j \) the particle +core states are: \( |0^+, j = j \rangle \), and \( |1^-, j', J = j \rangle \). The two states form a parity doublet, they have the same spin but opposite parity. A weak parity and time reversal violating interaction \( V_{PT} \) will mix the two doublet states. Taking for the weak interaction a form:

\begin{equation}
V_{PT} = f(r) \boldsymbol{r} \cdot \boldsymbol{\sigma} \tag{3}
\end{equation}

where \( f(r) \) is a function of \( r \). Choosing for \( f(r) \) a function proportional to:

\( \left( r^2 - \frac{5}{3} \langle r^2 \rangle \right) \) one can write \( V_{PT} \approx \boldsymbol{S} \cdot \boldsymbol{\sigma} \).

One then finds \cite{1} that the Schiff moment is proportional to the inverse energy weighted sum of the Schiff operator:

\begin{equation}
|S| \sim \sum_{i} \frac{|(1^-|S|0^+)|^2}{\Delta E_i} \tag{4}
\end{equation}

(A precise expression for \( S \) can be found in reference \cite{1}. \( \Delta E_i \) are the excitation energies of the \( 1^- \) states. Experiments indicate some of the dipole strength is found at low-energies thus enhancing the inverse energy weighted sum. One therefore expects that the above mechanism will contribute significantly to the nuclear Schiff moment. It is important to study the distribution of ISD in spherical nuclei. Such a study is presented in the next section.

3. RPA calculations

A fully self-consistent HF-based RPA calculations of the strength distributions of the electric isoscalar and isovector dipole excitations in a wide range of spherical nuclei was performed, using the effective Skyrme type interaction. In order to insure self-consistency the calculations were carried out using a large p-h space and included all the terms of the p-h residual interaction (time-even and time-odd) which are associated with the energy density functional used in the HF calculations.

For a given probing operator \( F_L \), we have calculated the strength function

\begin{equation}
S(E) = \sum_j |\langle 0|F_L|j \rangle|^2 \delta(E_j - E_0) \tag{5}
\end{equation}

Here, \( |0\rangle \) is the RPA ground state and the sum is over all RPA excited states \( |j \rangle \) with the corresponding excitation energies \( E_j \). We adopt the single particle scattering operator

\begin{equation}
F_L = \sum_{iM} f(r_i) Y_{LM}(i) \tag{6}
\end{equation}
for isocalar \((T = 0)\) excitations and

\[
F_L = \frac{Z}{A} \sum_n f(r_n) Y_{LM}(n) - \frac{N}{A} \sum_p f(r_p) Y_{LM}(p),
\]

(7)

for isovector excitations \((T = 1)\). We then determine the energy moments of the strength function,

\[
m_k = \int_0^\infty E^k S(E) \, dE.
\]

(8)

The centroid energy, \(E_{\text{CEN}}\), is then obtained from

\[
E_{\text{CEN}} = \frac{m_1}{m_0}.
\]

(9)

We will present the results for the isocalar dipole using:

\[
f(r) = r^3 - (5/3)(r^2)r,
\]

as the probing operator. Note, for the ISD the second term in \(f(r)\) is added in order to insure zero contribution from the spurious state, associated with the center of mass motion.

We also performed calculations for the isovector dipole (IVD) resonance with an operator

\[
D = \sum_i (r_i^2 - \frac{5}{3} \langle r^2 \rangle) \epsilon_i \tau_{zi}.
\]

(10)

However as shown in [1] the isovector part of the Schiff moment has other contributions that are not proportional to the strength of the IVD but involve the amplitudes of the IVD. Therefore when considering the IVD strength contribution to the atomic dipole measurements one should keep this in mind. Apart from the role played by the ISD and the IVD strength distributions in the calculation of the nuclear Schiff moment, there is general interest in the properties of the isocalar giant dipole resonance (ISGDR) and the overtone of the isovector giant dipole resonance (OIVGDR) and in particular in the low energy components the ISD and IVD strength distributions.

4. Results

In this section the results of the HF based RPA calculations of the strength distribution, \(S(E)\), the strength function divided by the energy, \(S(E)/E\) and the inverse energy weighted sum of the strength distribution, \(m_{-1}\), of the ISD and IVD, for a wide range of nuclei, are presented. We should stress that the reason we present in each case the inverse energy weighted strength distribution, in addition the strength distribution, is the fact the Schiff moment depends on the inverse energy weighted sum [1]. We are concentrating on the low-energy region where the \(S(E)/E\) is large. We also include results for the centroid energies of isocalar giant dipole resonance (ISGDR) and the overtone of the isovector giant dipole resonances (OIVGDR). The calculations were carried out for 18 frequently used Skyrme type interactions. Using the probing operator of Eqs. (1), we display in Figures 1 and 2 the HF-based RPA results for the strength function \(S(E)\) of the ISD in \(^{40}\text{Ca},^{48}\text{Ca},^{50}\text{Ni},^{60}\text{Ni}\) and \(^{78}\text{Ni}\) (Figure 1) and in \(^{90}\text{Zr},^{96}\text{Zr},^{104}\text{Zr},^{144}\text{Sm},\) and \(^{208}\text{Pb}\) (Figure 2), calculated using the KDE0v1 Skyrme interaction [5] that is representative of the strength distributions for the rest of the interactions. Note the strong enhancement in the ISD strength distributions at low energy in the neutron rich nuclei.
Fig 1. HF-based RPA results for the distribution of the strength function, \( S(E) \), of the isoscalar dipole, for the \( ^{40}\text{Ca}, ^{48}\text{Ca}, ^{56}\text{Ni}, ^{68}\text{Ni} \) and \( ^{78}\text{Ni} \) nuclei, calculated using the KDE0v1 Skyrme interaction [5]. An excitation energy range of 0-60 MeV and Lorenzian smearing of a 2 MeV width were used in the calculation.

In Figures 3 and 4 are displayed the HF-based RPA results for the strength function divided by the energy, \( S(E)/E \), of the ISD, obtained in \( ^{40}\text{Ca}, ^{48}\text{Ca}, ^{56}\text{Ni}, ^{68}\text{Ni} \) and \( ^{78}\text{Ni} \) (Figure 3) and in \( ^{90}\text{Zr}, ^{96}\text{Zr}, ^{104}\text{Zr}, ^{144}\text{Sm}, \) and \( ^{208}\text{Pb} \) (Figure 4) calculated using the KDE0v1 Skyrme interaction [5]. Note the relatively large contribution to moment \( m_{-1} \) from the low energy region, in particular in the case of neutron rich nuclei.

In Table 1 we display the values of the centroid energies, \( m_1/m_0 \) (in MeV) for the ISGDR, obtained using the probing operator of Eqs.(1) and the OIVGDR, obtained using the probing operator of Eqs.(10), for a wide range of nuclei. The KDE0v1 Skyrme interaction [5] was used in the calculations. The ISGDR and OIVGDR are calculated over the excitation energy ranges, 16 – 40 and 20 – 60 MeV, respectively. Note the significant enhancement in the values of the inverse energy moment \( m_{-1} \), in neutron rich isotopes which is associated with the increase in the ISD and IVD strengths at low energy.

Considering, for example, the case of \( ^{208}\text{Pb} \), we find that the centroid energies of the ISGDR and the OIVGDR are 24.5 and 35.2 MeV, respectively. The values of the inverse energy moment are \( m_{-1} = 17737 \) and \( 1806 \text{ fm}^6 \text{ MeV}^{-1} \) for the ISD and the IVD in \( ^{208}\text{Pb} \), respectively. The value of \( m_{-1} \) for the IVD is only about 10% of that of the ISD. The findings for this nucleus are consistent with the estimate found for the Schiff moment in ref. [1]. Using the expressions for the weak interaction part from the above reference we find that the contribution to the Schiff moment
considered here, is as large as the result obtained using the single particle models (see for example [6] and references therein)

Fig. 3. Self-consistent HF-based RPA results for the distribution of the strength function divided by the energy, S(E)/E, of the isoscalar dipole, for the 40Ca, 48Ca, 56Ni, 68Ni and 78Ni nuclei, calculated using the KDE0v1 Skyrme interaction [5]. An excitation energy range of 0-60 MeV and Lorenzian smearing of a 2 MeV width were used in the calculation.

Fig. 4. The same as Fig. 3 but for nuclei listed in the figure.

5. Summary

We have presented results of HF-RPA calculations with Skyrme type interactions, for the strength functions and corresponding inverse energy moments of the isoscalar dipole (ISD) and isovector dipole (IVD) for various nuclei using a probing operator which is the same as the Schiff operator up to a normalization. We see that the contribution of the IVD to the Schiff strength distribution in the even-even nucleus is smaller by an order of magnitude than that of the ISD. We find that in exotic nuclei with a large neutron excess the ISD and the IVD strength distributions is pushed to lower energies and thus increasing considerably the inverse energy moment $m^{-1}$ of the strength distribution. In particular this means that the ISD contribution to the Schiff moment in the odd-even nucleus might be further enhanced. We also find that the contribution of the isovector inverse energy Schiff distribution in the even-even nucleus is smaller than that of the isoscalar by an order of magnitude.

The distributions of low-lying dipole strength (both isoscalar and isovector) are presently the subject of a large number of experimental studies. Our work provides a theoretical description of these distributions for a wide range of nuclei. Moreover, the various studies in the past, (except reference [1]), have not addressed the question, of the relation between the low-lying dipole strength and the Schiff moment, a quantity that is central to atomic studies of time reversal violation.
This relation is emphasized and discussed in this presentation. Future experiments that will measure static electric dipole moments using exotic atoms with large neutron excess spherical nuclei will need to use theoretical input in order to relate the results obtained to the limits of time reversal conservation. The results of the present study will be of help in this respect.

|      | ISGDR | OIVGDR |
|------|-------|--------|
| $^{40}\text{Ca}$ | 27.9  | 38.4   |
| $^{48}\text{Ca}$ | 29.0  | 39.6   |
| $^{56}\text{Ni}$ | 28.5  | 39.5   |
| $^{68}\text{Ni}$ | 28.4  | 38.5   |
| $^{78}\text{Ni}$ | 28.2  | 39.6   |
| $^{90}\text{Zr}$ | 28.0  | 38.2   |
| $^{96}\text{Zr}$ | 27.4  | 37.5   |
| $^{104}\text{Zr}$ | 26.9  | 37.5   |
| $^{100}\text{Sn}$ | 27.7  | 38.5   |
| $^{144}\text{Sm}$ | 26.3  | 36.9   |
| $^{208}\text{Pb}$ | 24.5  | 35.2   |

Table 1. Values of the centroid energies, $m_1/m_0$ (in MeV) for the ISGDR, using the probing operator of Eqs. (1), and the OIVGDR, using the probing operator of Eqs. (10), for a wide range of nuclei, calculated using the KDE0v1Skyrme interaction [5]. The ISGDR and OIVGDR are calculated over the energy ranges of 16 – 40 MeV and 20 – 60 MeV, respectively.

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