Evidence of Residual Strong Interaction at Nuclear-Atomic Level via Isotopic Shift in LiH-LiD Crystals

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Artificial activation of the strong interaction by adding one neutron to the nucleus causes the global reconstruction of the macroscopic characteristics of solids. The experimental evidence of macroscopic manifestation of the strong interaction in the optical spectra of solids which differ by one neutron from each other (using LiD crystals instead LiH ones) is presented for the first time. As far as the electromagnetic and weak interactions are the same in both kind of crystals, it only changes the strong interaction, therefore the renormalization of the energy of electromagnetic excitations (electrons, excitons, phonons) is carried out by the strong nuclear interaction. The necessity to take into account some new residual inter-relations between strong and electromagnetic interactions are underlined. An interpretation of the isotopic shift caused by the addition of one neutron is also discussed. From the experimental value of the isotopic shift we obtain a residual strong coupling constant equal to 2.4680.

1 Introduction

To the present we have a clear picture about the different kind of interactions and their main scenarios: electromagnetic ones for the realm of atomic physics and strong interactions for nuclear physics [1, 2]. However, in this articles we would like to report about some new experimental evidence, together with a tentative theoretical interpretation, pointing towards some relationship between both kind of interactions, which seems to lead to a new understanding in which nuclear forces can reach outside the nucleon boundaries and manifest themselves at the atomic level, at least in the magnetic manifestation. In what follows we shall try to explain how residual strong like interactions can affect, via electronic excitations (electrons, excitons, phonons) through isotopic effects, the binding energy of the dielectrics LiH and LiD crystals [3].

Nowadays in text books and elsewhere the separation of electromagnetic and strong interactions is tacitly assumed. Our results shine a new light on some residual interaction (ultimately based in the character of magnetic forces, of electromagnetic or color origin, which by their very nature, are difficult to conceal within the elusive nucleon physical boundary) between both kind of forces which is experimentally manifested trough isotopic shift. We hope that the results that we report in this paper will give a new insight about the manifestation of nuclear forces, by isotopic shift, beyond the nuclear domain.

2 Experimental results

In this part we shall describe the results of the optical spectroscopy of isotope-mixed solids (see, also [3]). The apparatus used in our experiments has been described in several previous publications [4, 5]. For clarity, we should mentioned here that immersion home-made helium cryostat and two identical double-prism monochromators were used. One monochromator was used for the excitation and the other, which was placed at right-angle to the first, for analyzing the luminescence and scattering of light. In our experiments we investigated two kinds of crystals (LiH and LiD) which only differ by the addition of one neutron. In view of the high hygroscopy of the investigated samples, the crystals were cleaved directly in liquid (superfluid) helium in the cryostat bath [4]. This makes possible to prepare samples with a clean surface. We found no changes in the free-exciton luminescence or resonance Raman scattering (RRS) [5] spectra when a sample with such a surface was studied for periods lasting 15 hours. The crystals were synthesized from 7Li metal and hydrogen 99.7 per cent purity and deuterium of 99.5 per cent purity (see, e.g. [3, 5] and references therein). We should remind very briefly about the electronic excitations in solids. According to modern concept, the excitons can be considered [6] as the excitation of the N-particles system: An electron from the valence band of insulators (see Fig. 1) is excited into the conduction band.

The attractive Coulomb potential between the missing electron in the valence band, which can be regarded as a positively charged hole, and the electron in the conduction band gives a hydrogen-like spectrum with an infinitive number of bound state and ionization continuum. In this article we call the bound states of electron-hole (e-h) pairs exciton states (exc), while we refer to ionized e-h pairs as free carriers. However, the expression free carriers does not imply that the effect of the strong Coulomb forces between electronic excitation could be neglected. Thus, an exciton state can be built by appropriate superposition of e-h pairs, which in a simple two-band model for cubic crystal symmetry is

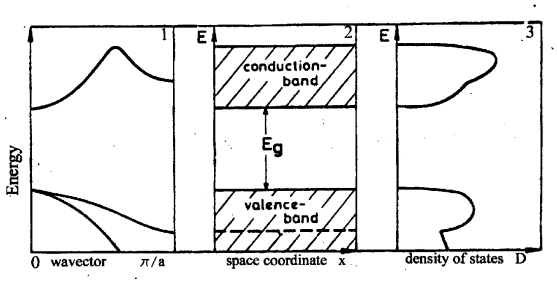

Fig. 1: Various possibilities to present the band-structure of homogeneous, undoped insulator (semiconductor). 1 - the dispersion relation, i.e. the energy E as a function of the wave vector, 2 - the energy regions of allowed and forbidden states as function of a space coordinate x and, 3 - the density of states (all curves are schematic ones).

given (for more details see [6]). As demonstrated some time ago [4] most low - energy electron excitation in LiH crystals are the large-radius excitons [6]. Exciton luminescence is observed when LiH (LiD) crystals are excited in the midst of the fundamental absorption. The spectrum of exciton photoluminescence of LiH crystals cleaved in liquid (superfluid) helium consists of a narrow (in the best crystals, its half-width is E $\leq$ 10 meV) phononless emission line and its broader phonon repetitions, which arise due to radiative annihilation of excitons with the production of one to five longitudinal optical (LO) phonons (see Fig. 2).

The phononless emission line coincides in an almost resonant way with the reflection line of the exciton ground state which is indication of the direct electron transition X_1 - X_4 of the first Brillouin zone [4].The lines of phonon replicas form an equidistant series biased toward lower energies from the resonance emission line of excitons. The energy difference between these lines in LiH crystals is about 140 meV, which is very close to the calculated energy of the LO phonon in the middle of the Brillouin zone and which was measured in (see, e.g. [3] and references therein). As we can see from Fig. 2 the photoluminescence spectrum of LiD crystals is largely similar to the spectrum of intrinsic luminescence of LiH crystals. The isotopic shift of the zero phonon emission line of LiH crystals equals 103 meV. There are, however, some related distinctions. Firstly the zero-phonon emission line of free excitons in LiD crystals shifts to the short-wavelength side on 103 meV. The second difference concludes in less value of the LO phonon energy, which is equal to 104 meV. Comparison of the experimental results on the luminescence and light scattering [3] in the crystals which differ by only one neutron is allowed to the main conclusion motivating this work: The addition of one neutron (using LiD crystals instead LiH ones) produce an unexpected increase of 103 meV in the exciton energy which seems rather difficult to explain within the conventional solid state physics scenario.

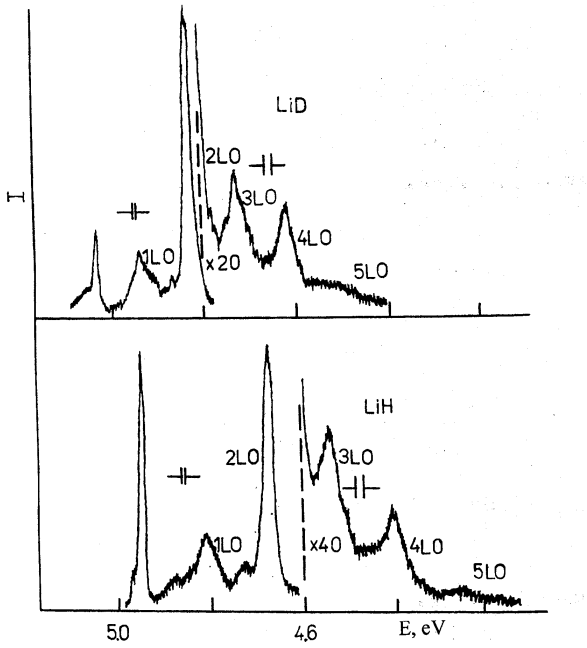

Fig. 2: Photoluminescence spectra of free excitons at 2 K in LiH and LiD crystals cleaved in superfluid helium.

3 Interpretation of the Isotopic Shift

We are used to find characteristic energies, mostly due to electrical interactions, of the order of one eV in the atomic and molecular scenarious. The reported experimental result of 0.103 eV emerging from magnetic-like interaction (magnetic forces are a factor v/c weaker than electric ones) is a surprising result pointing towards something that has not been observed before. The following comments, although tentative, pretend to give a plausible physical picture of new dynamical effects extending beyond the undefined borders of nucleons. From many experiments in QCD we know that direct forces between quarks are strong color analogues of electrostatic forces. However, in QCD, like in all gauge theories formulated within the context of special relativity, magnetic effects are unavoidable. In its more simple-minded description, electrostatic-like interactions between quarks have an origin and sink in the individual quarks confined in a nucleon. However, since quarks are not at rest, magnetic-like effects have to arise. The question we now ask is whether these effects should be limited to the inside-nucleon region or, perhaps, propagate outwards. In the absent of magnetic monopoles, magnetic force lines are closed. Moreover, magnetic fields are related to the SO(3) rotation group and its SU(2) covering group and it is not evident, at least in principle, if they couple only to ordinarily charged particles (remember that the SU(2) group is also contained in SU(3)). Consequently, in what follows, we shall consider, as an Ansatz, that magnetic color like

forces also couple to charged leptons. From the experimental results described before which arise by adding a single neutron to the LiH crystal:

$$LiH + n \longrightarrow LiD.$$

It seems that the 0.103 eV value should be regarded as an isotopic shift attributed to the magnetic moment of the charge-neutral neutron.

We are already familiar with the dipole-dipole magnetic interaction arising from the hyperfine splitting in the Hydrogen atom (for an adequate, to our purpose, study see [7]). The ground state wave function for the electron in the Hydrogen atom, including the spin part, is

$$\psi_0 = (\pi {a_0}^3)^{-1/2} e^{-r/a_0} |s>, \tag{1}$$

a_0 being the Bohr radius. We also need the energy of a magnetic dipole $\vec{m}_1$ in a magnetic field $\vec{B}$ produced by another dipole ($\vec{m}_2$) given by

$$H = -\vec{m}\,\vec{B}.$$

$$H = -\frac{1}{4\pi}\frac{1}{r^3}\left[3(\vec{m}_1\hat{r})(\vec{m}_2\hat{r}) - \vec{m}_1\,\vec{m}_2\right] - \frac{2}{3}(\vec{m}_1\,\vec{m}_2)\delta^3(\vec{r}). \tag{2}$$

As is well known, for s states with spherical symmetry the first term vanishes and only the second term involving a delta function contributes. This is essential as the wave function (1) has a finite value for $r = 0$ so that the energy comes out from a contact-interaction (see [7]). The magnetic dipole-dipole interaction can thus be treated as a perturbation. In first order perturbation theory:

$$E' = \int {\psi_0}^* H \psi_0 dV. \tag{3}$$

As mentioned, only the second term contributes giving:

$$E' = -\frac{2}{3} < \vec{m}_1\,\vec{m}_2 > |\psi_0(0)|^2 = -\frac{2}{3}\frac{1}{\pi {a_0}^3} < \vec{m}_1\,\vec{m}_2 > . \tag{4}$$

For the electron-proton we have two configurations according to the spin of both particles:

$$\vec{m}_1 = \gamma_p \vec{S}_p, \qquad \vec{m}_2 = -\gamma_e \vec{S}_e.$$

(γ: gyromagnetic ratio; $\gamma = (e/2m)g$, the g-factor being 2.0023 for the electron and 5.5857 for the proton.)

According to equation (4), we obtain for the triple and singlet states in Hydrogen, the energies

$$E'_t = \frac{1}{3}\frac{e^2}{a_0^3 m_e M_p} g_p = 1.4685 \times 10^{-6}\ \text{eV}$$

and

$$E'_s = -\frac{e^2}{a_0^3 m_e M_p} g_p = -4.4054 \times 10^{-6}\ \text{eV},$$

with a gap $\Delta E' = 5.874 \times 10^{-6}$, coincident with the hydrogen hyperfine splitting experimental result.

Similar calculations can be easily carried out for Deuterium (spin 1 and gyromagnetic ratio $g_d = 1.71$) with the results:

$$E'_{3/2} = 4.4980 \times 10^{-7}\ \text{eV},$$

$$E'_{1/2} = -8.9960 \times 10^{-7}\ \text{eV},$$

$$\Delta E'_d = E'_{3/2} - E'_{1/2} = 1.3494 \times 10^{-6}\ \text{eV}.$$

Turning now to the *Isotopic shift* issue, from the above values, we have four alternatives depending on the relative spins, however, as the lowest energy for both LiH and LiD is the corresponding to singlet states, we shall choose:

$$\Delta E = (E'_s)_H - (E'_{1/2})_D = -3.5058 \times 10^{-6}\text{eV}, \tag{5}$$

far from the experimental 0.103 eV. Next we shall assume that the experimental isotopic shift of 0.103 eV is the result of the onset of a residual strong interaction when the neutron is added, accordingly we do not modify $(E'_s)_H$ but modify $(E'_{1/2})_D$ in the following way: In Hydrogen the absolute value of the charge is the same so that in electric or magnetic interactions the coupling constant is $\alpha = e^2$. However, as the neutron do not have electric charge, in the dipole magnetic interaction the effective coupling constant can be defined through the transformation

$$\alpha = e^2 \longrightarrow (\alpha_s)_{\text{eff}} = e\, e_s. \tag{6}$$

The Bohr radius is thus modified:

$$a'_s = \frac{1}{e\, e_s}\frac{1}{m_e}.$$

From (4), it is easy to obtain

$$(E'_{1/2})_D = -\frac{4}{3} g_d \frac{(\alpha'_s)^4 m_e^2}{M_d}. \tag{7}$$

Inserting in (5) the 0.103 experimental value for ΔE and solving for α'_s, we obtain:

$$\alpha'_s = 0.1342,$$

and a *strong charge*

$$e_s = \frac{0.1342}{0.08542} = 1.5710,$$

leading to a strong coupling constant $e_s^2 = \alpha_s = 2.4680$. Quite large in comparison with the normal fine structure constant.

4 Conclusions

The experimental evidence of the macroscopic manifestation of strong nuclear interaction in optical spectra of solids which are differing by one neutron from each other has been presented for the first time. This evidence is based on two independent experimental results, which is directly seen from luminescence and reflection spectra. Our interpretation is based in the neutral charge of the neutron which in turn is responsible for the observed isotopic shift. We should be aware of the delicate interplay between solid state physics translated for a theoretical interpretation to the nuclear and subnuclear background which we have tried to accomplish in a way that could be regarded as somewhat tentative but unavoidable given the uncertainties laying in the strong magnetic-like interaction between nucleons and electrons.

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