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# Phenomenology of the Origin of Isotope Effect

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***Author's contribution***

*The sole author designed, analyzed and interpreted and prepared the manuscript.*

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## ABSTRACT

Our paper describes the macroscopical manifestation of the origin of isotope effect via spectroscopic study of the reflection and luminescence spectra of LiH and LiD crystals which are differ by term of one neutron from each other. The experimental results demonstrate the direct evidence of the strong nuclear interaction. Inasmuch as the gravitation, electromagnetic and weak interactions are the same in both of kind crystals, it only changes the strong interaction. Therefore a sole deduction is made that the renormalization of the energy of electromagnetic excitations (electrons, excitons, phonons) is carried out by the strong nuclear interaction. The last one simultaneously indicates the origin of the isotope effect is caused by the strong nuclear interaction. The necessity to take into account the more close relation between quantum chromodynamics and quantum electrodynamics is underlined. In the first step the quantum electrodynamics should be taken into account the strong interaction at the description of the dynamics of elementary excitations (electrons, excitons, phonons) dynamics in solids.

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# 1 INTRODUCTION

Recently it was shown the direct dependence of the energy of interband transition $E_g$ in solids (for example $LiH_xD_{1-x}$ crystals) on the strong nuclear interaction [1]. The present paper is devoted to advance description of the experimental results demonstrated indicated above dependence. According to contemporary physics, the Universe is made up of matter fields, whose quanta are fermions and force fields, whose quanta are bosons. Basically, fermions can be classified into two groups: elementary and composite fermions. Elementary fermions are leptons (electron, electron neutrino, muon, muon neutrino, tau, and tau neutrino and quarks (up, down, top, bottom, strange and charm)) (see, Table 1). Hadrons (neutrons, protons) containing an odd number of quarks, and nuclei made of an odd number of nucleons (for example $^{13}_{6}$C nuclei contain six protons and seven neutrons) are considered to be composite fermions. Elementary fermions are the fundamental building blocks of matter and antimatter [2,3].

**Table 1. Quarks and leptons**

| | Family 1 | 2 | 3 | Electric charge (e) |
|---|---|---|---|---|
| . Leptons | $e^-$ | $\mu^-$ | $\tau^-$ | - 1 |
| | $\nu_e$ | $\nu_\mu$ | $\nu_t$ | 0 |
| Quarks | u | c | t | 2/3 |
| | d | s | b | - 1/3 |

Bosons are identical particles having zero or integer spins. As fermions, bosons can be categorized into two groups: elementary and composite bosons. Unlike fermions, bosons do not obey the Pauli Exclusion Principle. In other words, any number bosons can occupy the same quantum state. Behaviors of bosons are described by the Bose - Einstein statistics. The SM [4] only consists of five elementary bosons (see Fig. 11 in [5]). They are namely the Higgs boson, gluon, Z and $W^{\pm}$ bosons. The Higgs boson have zero electric charge and zero spin is the only scalar boson.

The discovery of the neutron by Chadwick in 1932 [2] may be viewed as the birth of the strong interaction: it indicated that the nuclei consists of protons and neutrons and hence the presence of a force that holds them together, strong enough to counteract the electromagnetic repulsion. In 1935, Yukawa [6] pointed out that the nuclear force could be generated by the exchange of a hypothetical spinless particle, provided its mass intermediate between the masses of proton and electron - a meson. Yukawa predicted the pion [2, 7]. The strong forces does not act on leptons (electrons, positrons, muons and neutrinos), but only on protons and neutrons (more generally, on baryons and mesons - this is the reason for the collective name hadrons). It holds protons and neutrons together to form nuclei, and is insignificant at distances greater than 10 $^{-15}$ m ([6] see however below). Its macroscopic manifestations are restricted up to now to radioactivity and the release of nuclear energy [3,4]. Quantum chromodynamics (QCD) is the theory of the strong interaction, responsible for binding quarks through the exchange of gluons to form hadrons (baryons and mesons).

Our present knowledge of physical phenomena suggests that there four types of forces between physical bodies (see, e.g. [8, 9]):

1) gravitational; 2) electromagnetic; 3) strong; 4) weak (see, e.g. Table 8 in [5]).

Both the gravitational and the electromagnetic forces vary in strength as the inverse square of the distance and so able to influence the state of an object even at very large distances. Gravitational is important for the existence of stars, galaxes, and planetary systems as well as for our daily life, it is of no significance in subatomic physics, being far too weak to noticeably influence the interaction between elementary particles [3, 4]. Electromagnetism is the force that acts between electrically charged particles (atoms, molecules, condensed matter). When nuclear physics developed, two new short

- ranged forces joined the ranks. These are the nuclear force, which acts between nucleons (proton, neutron, etc.) and the weak force, which manifests itself in nuclear $\beta$ - decay (see, e.g. [7]. The nuclear force is a result of the strong force binding quarks to form protons and neutrons. Due to experimental results of this paper connected to the manifestation of the strong interaction, we should briefly analyze the structure of subatomic particles and the strong interaction. We should underlined, that subatomic physics lacks so coherent theoretical formulation that would permit us to analyze and interpret all phenomena in a fundamental way: atomic physics has such a formulation in quantum electrodynamics, which permits calculations of some observable quantities to more than six figures. Subatomic physics deals with all entities smaller than the atom.

The modern quantum mechanical view of the three fundamental forces (all except gravity) is that particles of matter (fermions neutrons, protons, electrons) do not directly interact with each other, but rather carry a charge, and exchange virtual particles (gauge bosons photons, gluons, gravitons) which are the interaction carriers or force mediators. As can be see from Table 8 in [5], photons are the mediators of the interaction of electric charges (protons, electrons, positrons); and gluons are the mediators of the interaction of color charges (quarks). In our days, the accepted view is that all matter is made of quarks and leptons (see Table 1). As can be see, of the three pairs of quarks and leptons, one pair of each - the quark u and d and the leptons $e^-$ and $\nu_e$ (electrons neutrino) - are necessary to make up the every day world, and a world which contained only these would seem to be quite possible.

The facts, summarized in the modern nuclear and subatomic physics (see, e.g. [2, 7]) allow to draw several conclusions in regard to nuclear forces, most notably that the binding energy of a nucleus is proportional to the number of nucleons and that the density of nuclear matter is approximately constant. This lead to conclude that nuclear forces have a "saturation property" [2, 7]. It seems from the last conclusion it is enough to change the number of neutrons in nucleus to change strength of nuclear force. But the last one constitutes the main ideas of the isotope effect [8].

# 2 EXPERIMENTAL

The apparatus used in our experiments has been described in several previous publications [10, 11, 9]. 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 are differ by a term of one neutron. Lithium hydride and lithium deuteride are ionic insulating crystals with simple electronic structure, four electrons per unit cell, both fairly well - described structurally (neutron diffraction) and dynamically (second - order Raman scattering) and through ab intio electronic structure simulations. Among other arguments, LiH and LiD are very interesting systems due to their externally simple electronic and energy band structures and to the large isotopic effects when the hydrogen ions are replaced by the deuterium ones. On the other hand, the light mass of the ions, specially H and D, makes that these solids have $E_g$ equals 4.992 eV for LiH and 4.095 eV for LiD at 2 K [8]. All three kinds of forces - gravitational, electromagnetic and weak are also the same for compounds above. The difference between these materials concludes at one neutron in the nucleus of deuteron.

The single crystals of LiH and LiD were grown from the melt by the modified method of Bridgeman - Stockbarger (see [12, 8] and references quoted therein). The crystals were synthesized from $^7$Li metal and hydrogen of 99.7% purity and deuterium of 99.5% purity. Virgin crystals fad a slightly blue - grew color, which can be attributed to nonstoichiometric excess of lithium present during the grown cycle. On annealing for several days (up to 20) at 500$^0$C under $\sim$ 3 atm of hydrogen or deuterium, this color could be almost completely eliminated. Because of the high reactivity and high hygroscopy of investigated crystals an efficient protection against the atmosphere was necessing. Taking into account this circumstance, we have developed special equipment which is allowed to prepare samples with a clean surface cleaving their in the bath of helium cryostat with normal or superfluid liquid helium [5]. The samples with such surface allow to preform measurements during 15 hours. An improved of LiH (LiD) as well as mixed crystals were used in the present study. In spite of the identical structure of all free - exciton luminescence spectra, it is necessary to note a rather big variation of the luminescence intensity of the crystals from the different batches observed in experiment.

# 3 RESULTS

We should remind very briefly about the electronic excitations in solids. According to modern concept, the excitons can be considered [13] as the excited of the N - particles system: An electron from the valence band (see Fig. 1 in [9]) 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 (Fig. 71 in [14]). Below we will briefly describe the results of the optical spectroscopy of isotope - mixed solids. In our experiments we have investigated the low - temperature optical spectra (reflection - Fig. 1 and luminescence Fig. 2) of $LiH_xD_{1-z}$ crystals ($0 \leq x \leq 1$) which are differ by term of one neutron from each other. The mirror reflection spectra of mixed and pure LiH and LiD crystals cleaved in liquid helium are presented in Fig. 1. All spectra have been measured with the same apparatus under the same condition. As the deuterium concentration increases, the long - wave maximum (n = 1S excitons [13]) broadens and shifts towards the shorter wavelengths.

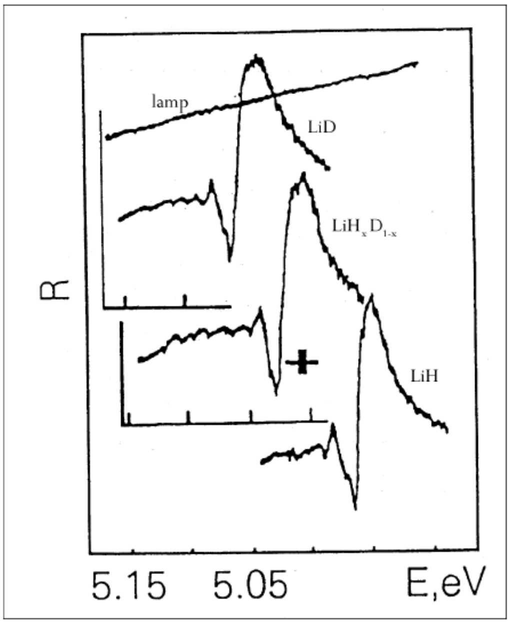


**Fig. 1. Mirror reflection spectra of indicated crystals. Light source without crystals indicates by lamp**

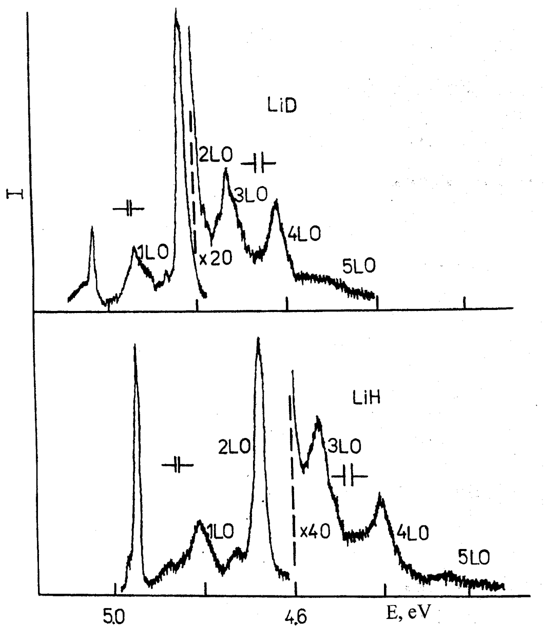


**Fig. 2. Photoluminescence spectra of free excitons at 2 K in LiH and LiD crystals cleaved in superfluid helium**

As demonstrated early (see, e.g. review [14]) most low - energy electron excitation in LiH crystals are the large - radius excitons [13]. 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 $\Delta E \leq 10$ 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 [15]. 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 [16, 17] and which was measured in (see, e.g. [18, 12] and references quoted therein). The isotopic shift of the zero - phonon emission line of LiH crystals equals 103 meV. 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. There are, however, some distinctions one is related.

Firstly the zero - phonon emission line of free excitons in LiD crystals shifts to the short - wavelength side on 103 meV. These results directly show the violation of the strong conclusion (see, e.g. [2, 7]) that the strong force does not act on leptons. The second difference concludes in less value of the LO phonon energy, which is equal to 104 meV. When light is excited by photons in a region of fundamental absorption in mixed $LiH_xD_{1-x}$ crystals at low temperature, line luminescence is observed (Fig. 3), like in the pure LiH and LiD crystals. As before [12], the luminescence spectrum of crystals cleaved in superfluid liquid helium consists of the relatively zero - phonon line and its wide LO replicas. For the sake of convenience, and without scarfing generality, Fig. 3 shows the lines of two replicas.

Usually up to five LO repetitions are observed in the luminescence spectrum as described in detail in [12]. In Fig. 3 we see immediately that the structure of all three spectra is the same. The difference is in the distance between the observed lines, as well as in the energy at which the luminescence spectrum begins, and in the half - width of the lines.

The simplest approximation, in which crystals of mixed isotopic composition are treated as crystals of identical atoms having the average isotopic mass, is referred to as virtual crystal approximation (VCA) [19]. Going beyond the VCA, in isotopically mixed crystals one would expect local fluctuations in local isotopic composition within some effective volume, such as that an exciton. As follows from Fig. 1, excitons in $LiH_xD_{1-x}$ crystals display a unimodal character, which facilitates the interpretation of their concentration dependence. Fig. 4 shows the concentration dependence of the power of strong nuclear interaction, i.e. dependence on the neutron concentration. In first approximation the mechanism of isotope shift will be connect with the neutron magnetic field of the deuterium nucleus (neutron) (will be published separately).

As can be seen from Fig. 4, VCA method cannot describe observed experimental results was shown early [12] this deviation from linear low (VCA approximation) is connected with isotope - induced disorder in isotope mixed crystals $LiH_xD_{1-x}$. According to Lifshitz [20] the isotopic disordering ought be classified as site disordering of the crystal lattice. Comparison the experimental results on the luminescence and reflection in the crystals which differ by a term of one neutron only is allowed to the next conclusions;

1. At the adding one neutron (using LiD crystals instead LiH ones) is involved the increase exciton energy on 103 meV.
2. At the addition one neutron the energy of LO phonons is decreased on the 36 meV, that is direct seen from luminescence and scattering spectra.

Both characteristics are macroscopic and very easy measures by modern rather simple and at moderate price experimental technique.

# 4 DISCUSSION

Nucleus is central part of an atom consisting of A - nucleons, Z - protons and N - neutrons. The atomic mass of the nucleus is equal Z + N (see Fig. 1 in [5]). A given element can have many different isotopes, which differ from one other by the number of neutrons contained in the nuclei [2, 7, 21]. Modern physics distinguishes three fundamental properties of atomic nuclei: mass, spin (and related magnetic moment) and volume (surrounding field strength) which are source of isotopic effect (see, also [12, 22]).

Below we should briefly consider some peculiarities of the physics of deuteron. Much of what we know about nuclear structure comes from studying not the strong nuclear interaction of nuclei with their surroundings, but instead the much weaker electromagnetic interaction, That is, the strong nuclear interaction establishes the distribution and motion of nucleons in the nucleus, and we probe that distribution with the electromagnetic interaction. as is well - known from classical electrodynamics, any distribution of electric charges and currents produces electric and magnetic fields that vary with distance in a characteristic fashion (see, e.g. [2, 7]). It is customary to assign to the charge and current distribution an electromagnetic multipole moment associated with each characteristic spatial dependence - the $1/r^2$electric field arises from the net charge, which we can assign as the zeroth or monopole moment; the $1/r^3$ electric field arises from the first or dipole moment; the $1/r^4$ electric field arises from the second of quadrupole moment and so on. The monopole electric moment is just the net nuclear charge Ze. The next nonvanishing moment is the magnetic dipole moment $\mu$. A circular loop carrying i and enclosing area A has a magnetic moment of magnitude $|\mu|$ = iA; if the current is caused by a charge e, moving with speed v in a circle of radius r (with period $2\pi$r/v), then $|\mu| = \frac{e}{(2\pi r/v)}\pi r^2 = \frac{evr}{2} = \frac{e}{2m}$ (l), where (l) is the classical angular momentum mvr [23]. From atomic physics we know that the quantity $\frac{e\hbar}{2m}$ is called a magneton. In the case $m = m_e$ ($m_e$ is electron mass) we have the Bohr magneton $\mu_B = 5.7884 \cdot 10^{-5}$ eV/T and if $m = M_p$ ($M_p$ is proton mass) we have the nuclear magneton $\mu_N = 3.1225 \cdot 10^{-8}$ eV/T. Above we have been considering only the orbital motion of nucleons. From quantum mechanics we know that protons and neutrons, like electrons, also have intrinsic or spin magnetic moments, which have not classical analog.

The measured spin of the deuteron is $\overrightarrow{I}$ = 1. Besides that we know that deuteron has its parity is even [7, 8]. The total angular momentum $\overrightarrow{l}$ of deuteron should be like

$$\overrightarrow{I} = \overrightarrow{S_n} + \overrightarrow{S_p} + \overrightarrow{l}, \qquad (1)$$

where $\overrightarrow{S_n}$ and $\overrightarrow{S_p}$ are individual spins of the neutron and proton. The orbital momentum $\overrightarrow{l}$ of the nucleons as they move about their common center of mass is $\overrightarrow{l}$. There are four ways to couple $\overrightarrow{S_n}$, $\overrightarrow{S_p}$ and $\overrightarrow{l}$ to get a total $\overrightarrow{I}$ = 1.

1. $\overrightarrow{S_n}$ and $\overrightarrow{S_p}$ parallel with $\overrightarrow{l}$ = 0.
2. $\overrightarrow{S_n}$ and $\overrightarrow{S_p}$ antiparallel with $\overrightarrow{l}$ = 1.
3. $\overrightarrow{S_n}$ and $\overrightarrow{S_p}$ parallel with $\overrightarrow{l}$ = 1.
4. $\overrightarrow{S_n}$ and $\overrightarrow{S_p}$ antiparallel with $\overrightarrow{l}$ = 1.

since we know that the parity of the deuteron is even and the parity associated with orbital motion is determined by $(-1)^l$ we are able to rule out some options the observed even parity allows us to eleminate the combination of spins that include $l$ = 1, leaving $l$ = 0 and $l$ = as possibilities (see also [7, 8, 24, 23]).

For deuteron, only two nucleons are involved therefore we can assume further that the total magnetic moment is simply the combination of the neutron and proton magnetic moment

$$\mu_D = \mu_n + \mu_p = \left(g_{S_n}\mu_N S_n\right)/\hbar + \left(g_{S_p}\mu_N S_p\right)/\hbar, \qquad (2)$$

where the gyromagnetic ratio for a free nucleon is $g_n$ = - 3.826085 $\mu_N$ for a neutron and $g_p$ = 5.585695 $\mu_N$ for a proton.

Here we have assumed that the structure of a bound nucleon inside a nucleus is the same as in its free state (see, however [5, 25, 26]). Taking into account the maximum values of spins $(+\frac{\hbar}{2})$ we get

$$\mu_D = \frac{1}{2}\mu_N\left(g_{s_n} + g_{s_p}\right) = 0.879804\ \mu_N. \qquad (3)$$

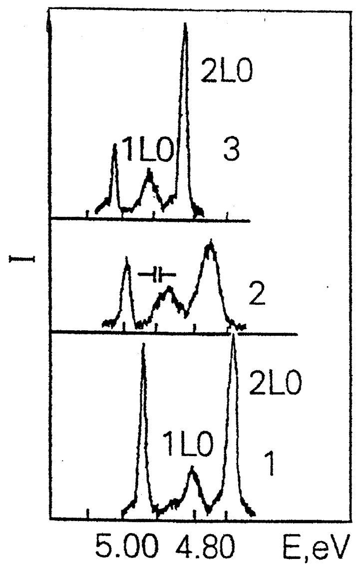


**Fig. 3. Photoluminescence spectra of free excitons in LiH (1), LiH$_x$D$_{1-x}$ (2) and LiD (3) crystals cleaved in superfluid helium at 4.2 K. Spectrometer resolution is shown**

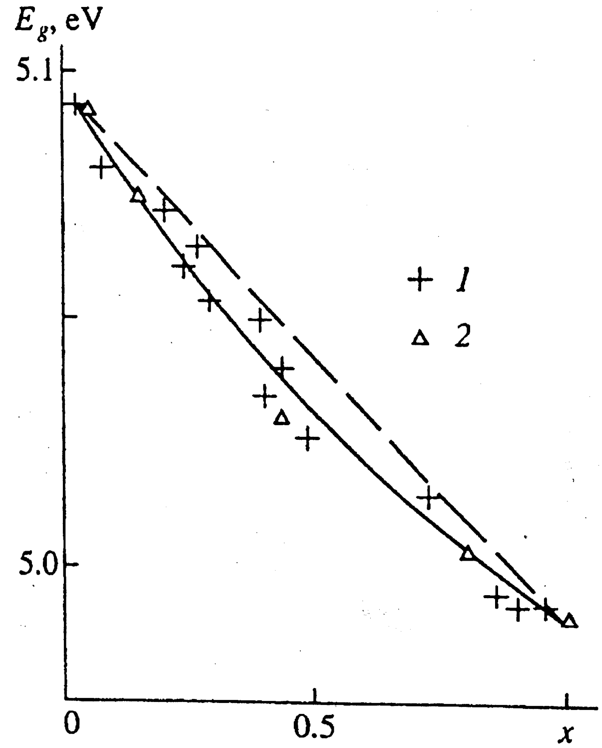


**Fig. 4. Dependence of the interband transition (strong interaction) energy $E_g$ in mixed crystals on the concentration x (number of neutrons N). The straight dashed line is the linear dependence of coupling constant strong interaction $\alpha_s$ = f (N) [$E_g$ = f (x)] in the virtual model. The solid line corresponds to calculation using the polynom of second degree $E_g = E_g(\mathrm{LiD}) + \{E_g(\mathrm{LiH}) - E_g(\mathrm{LiD}) - b\}x - bx^2$, where b = 0.046 eV is curvature parameter [12]. Points derived from the reflection spectra indicated by crosses, and those from luminescence spectra by triangles.**

The observed value is $0.8574376\mu_N$ in good but not quite exact agreement with calculated one. Usually this tiny discrepancy describes to take into account a small mixture of D state ($l$ = 2) in the deuteron wave functions. Calculating the magnetic moment of deuteron from this wave function gives that deuteron is 96 per cent $l$ = 0 (s orbit) and 4 percent ($l$ = 2) (d orbit). Independent evidence for this fact comes from the observation that the deuteron has a small, but finite, quadrupole moment Q = 0.29 fm $^2$(see, also [23, 27]). The last one points to the tensor character of the nucleon - nucleon interaction (the more details see, e.g. [2, 7]). Nuclear magnetic dipole and electric quadrupole have a similar importance in helping us to interpret the deuteron structure (see, also [24]).

The interaction energy of the electron magnetic moment and nucleus magnetic field is given by the well - known formula(see, e.g. [28]):

$$E = \vec{\mu}_I \cdot \vec{B}_e. \tag{4}$$

Typical energy differences of hyperfine multiplets are only about $10^{-7}$ eV (in case of the deuteron it is $3.16 \cdot 10^{-7}$ eV (see also [29]). This value is by more than seven order less than we observe in experiments: the isotopic shift of the n = 1s excitons is equal to 0.103 eV.

The short range character of the strong interaction doesn't possess direct mechanism of the elementary excitation energy renormalization, which was observed in the experiments. However, there is one not very convincing possible hypothesis of the strong interaction mechanism - this is residual long range electromagnetic interaction of the electric charge quarks [25]. The non - zero value of electric quadrupole moment in deuteron indicates in favour of this hypothesis, for example, in deuterium. Such hypothesis doesn't contradict to the conclusion of the papers [ 4, 26, 30] about the mass difference origin between the neutron and proton connected with electric charged u and d quarks (see, also [31]). Moreover, the neutron mass diminishing in nuclei in comparison to the free state of neutron independently shows the actual residual electromagnetic interaction in nucleons between quarks (see, also [32, 33]). Naturally, the origin of Van der Waals or new type forces* are in need of more quantitative not only experimental but also theoretical investigations of observed effects.

Nevertheless, we have very close of the isotope shift exciton energy in the case $^{12}C_x^{13}C_{1-x}$ diamond crystals to the indicated value above in LiH crystals. Indeed, in such experiments we have isotope shift in $^{12}C_x^{13}C_{1-x}$ diamond crystals approximately 15 meV (see, e.g. [8]) per one neutron and on seven neutrons we get 15 $\cdot$7 = 105 meV. This value is very close to the observed one (103 meV) in LiH crystals.

Thus, the tentative interpretation of describing experimental results don't find consistent explanation at the change strong interaction leaving it to be another mystery of SM (see, also [30]). We should remind that intrinsic contradiction of SM is already well - known. Really, the Lagrangian of QCD (theory of the strong interaction) describes both free motion and interaction between quarks and gluons, which is defined by the strength couple g, its eigenstates are the quarks and the gluons which are not observed in free states [4, 34]. The observed hadrons in the experiment don't eigenstates in QCD. It is obvious to expect that the modern theory of QCD should finally overcome these difficulties [34]. We should add that the current theoretical and experimental evidence for the existence of electronic objects with a fractional of electron charge (e/2, e/3, etc.) is reviewed in paper [35]. One more possible mechanism the influence of the strong interaction on the dynamics of elementary excitation connects with the zero - point vibration [7, 8]. Moreover it is necessary to take into consideration anomalous magnetic moments of nucleons. According to contemporary physics, the Universe is made up of matter fields, whose quanta are fermions and force fields, whose quanta are bosons. All these fields have vacuum fluctuation and zero - point energy. Experimental observation of the manifestation of strong nuclear interaction in the optical spectra of solids opens an avenue to new physics.

# 5 CONCLUSION

The artificial activation of the strong nuclear interaction by adding one (two or more) neutrons in atomic nuclei leads it to the direct observation of the strong interaction in low - temperature optical spectra of solids. This conclusion opens new avenue in the investigation of the strong nuclear interaction by means the condensed matter a like traditional methods (including accelerating technique). Experimental observation of the renormalization of the elementary excitation energy of solids by the strong nuclear (magnetic - like via gluons of neutrons) interaction stimulates its count in the process of description of the elementary excitations dynamics in quantum electrodynamics. Present article continuous to develop between nuclear and condensed matter physics. The main conclusion of the present article that the origin of the isotope effect is carried out by the strong nuclear interaction. In our paper is underlined the insufficient of the Standard Model.

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*) More than the half - century ago Foldy [36] was shown that the neutron - electron interaction energy equals approximately 1.4 eV (see, also [37]). The last value is on the one order more than the value observed in experiments equals 0.103 eV. In the case of the Coulomb electromagnetical neutron - electron interaction the neutron (quark) must have only approximately

1.3 % of necessary electron charge. The availability of the electrical charge of neutron is small in our estimation, though not equal to zero and does not contradict the papers results [25, 38] where was shown that $G_E^n(0) \neq 0$ (see also [39 - 41]).

# COMPETING INTERESTS

Author has declared that no competing interests exist.

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