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Nonlinearity of the Strong Coupling Constant in the Mass Isotope Effect

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Abstract
The measured isotopic shift of the zero - phonon emission line of free excitons in low - temperature (2 K) spectra of intrinsic luminescence of LiD crystals made it possible for the first time to obtain not only the value of the neutron - electron binding energy, but also its dependence on the distance between the proton and neutron in the deuterium nucleus. The obtained nonlinear dependence of the strong interaction coupling constant on the neutron - electron binding energy is associated with the manifestation of a new force in the mass isotope effect, previously not observed. The need for further theoretical investigation of nucleon dynamics in nuclear physics is emphasized.

Keywords: Strong Interaction, Hadrons, Quarks, Gluons, Excitons, Phonons, QED, QCD.

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Intrdouction

A common place in theoretical physics the idea that nuclear physics (NP) and elementary particle physics (high energy physics) that the initial blocks of matter in a uniform matter. The main goal of elementary particle physics (EPP) is to study the smallest structural elements of the surrounding world and the fundamental forces acting between them. Atomic physics studies the atom, which consists of a nucleus and light electrons revolving around it.

NP teaches after Chadwick's discovery of the neutron; nuclei consist of nucleons - protons and neutrons [1]. The stable state of the nucleus is due to the strong non electromagnetic interaction between nucleons, introduced by Yukawa in 1935 [2]. The static nature of the Yukawa potential cannot describe the spatial propagation of the strong interaction. Moreover, the short - range (= 10^{-15} m) indicates the absence of neutron - electron interaction. Perhaps, for this reason, all books on NP and EPP emphasize the absence of the influence of hadrons on leptons [3, 4]. Historically, such a picture corresponded to weak electromagnetic interaction of point charges of the proton, which was many orders of magnitude weaker than the strong interaction in the Yukawa picture. However, the results of experiments by Hofstadter and co – workers [5] showed that the electric charge in proton is not a point, but rather that there is a fine structure in the proton (see, also [6]) and thus demonstrated different balance of forces in the atomic nucleus [5-8]. In 1964, the existence of quarks in nucleons was independently proposed by Gell - Mann and Zweig taking into account the experimentally found inhomogeneity of nucleons in the atomic nucleus [7-9]. From quantum chromodynamics (QCD), 6 different flavors of quarks are known: up, down, storage, charm, top and bottom [4, 9]. The isotopic effect - the only effect whose degree of freedom is related to mass - was observed more than century ago in the line of lead atoms [14]. Until 60s of the last centuries, it was common place to divide Mendeleev's Table into 3 groups:

1. Light elements with Z ≤ 30 had a purely mass isotope shift.
2. Heavy elements with Z ≥ 58 had only a field effect, associated with a change in the radius of the nucleus in the isotope shift.
3. Between these two regions, the chemical elements had a small isotopic shift, since the mass and field contributions have opposite signs [10, 15, 16].

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Phenomenologically, the mass isotopic shift is described by the correction of the kinetic energy of atomic electrons by the motion of the nucleus and is described by the following relationship:

$$E = \frac{1}{2}\left(\frac{1}{m_e} + \frac{1}{M}\right)\sum_i p_i^2 + \frac{1}{M}\sum_{i \neq j} p_i p_j. \quad (1)$$

Here m_e and M are the mass of the electron and the nucleus, p_i and p_j are the momenta of the i - th and j - th electrons. It is the first term of relation (1) that describes the isotopic shift in light elements. The second term describes the specific mass isotope shift and is due to the electron's interaction [15]. The isotopic shift of heavy elements (field shiift) is caused by the difference in volumes (radii of nuclei) 0f different isotopes [16]:

$$\nu_i^{AA'} = \nu_i^{A} - \nu_i^{A'}, \quad (2)$$

where ν^A_i is the frequency isotopic shift of isotopes A (ν^A_i is transition frequency) and A' ($\nu^{A'}_i$ is transition frequency too). As already mentioned above a common feature of the Standard Model (SM) of modern physics is the absence of influence of the strong nuclear interaction on leptons (electron) [4, 9]. Following this statement we should not observe the effect of the added neutron in the atomic nucleus of isotope. This conclusion contradicts the history of the development of the isotope effect [15, 16]. The first description of the neutron - electron interaction was made in work [11, 12]. In 1936, Condon pointed out that the existence of neutron - electron interaction is manifested in the isotopic shift of lines in optical spectra, which was first observed in the spectra of lead isotopes [13-16]. The existence of a weak attraction of a neutron to an electron was described in a series of paper by Foldy [17, 18]. He pointed out that neutron- electron interaction has two contributions: the first is associated with the anomalous value of the neutron's magnetic moment, and the second is due to the internal Darwin coefficient - the electron's electric field [19]. This picture was justified by the mean theory of those years, and both mechanisms had an electromagnetic origin. We add that the first estimate in electrostatic model of the neutron - electron bond energy equal 106.7 meV was made in work, where the importance of studying the isotope effect for NP was also emphasized [20].

The discovery of global changes in macroscopic, including optics, properties upon the addition of one neutron made the unique crystals of LiH and LiD (diamond, graphene), which differ by one neutron, an excellent model for studying the strong interaction [21]. Indeed, in both crystals the lithium ions, protons and electrons are the same, and therefore the gravitational, electromagnetic and weak interaction are the same and the addition of one neutron, according to Yukawa, generates a strong interaction between the proton and the neutron in the deuterium nucleus, the influence of which on the electron (lepton) is manifested in the observed isotopic shift of zero - phonon line in low - temperature luminescence spectra of LiD crystals. We have previously emphasized the importance of using low - temperature spectroscopy to study strong nuclear interaction [22]. Let us add in this regard that a recently published sensible, informative review the author adheres to the already traditional direction of searching for new physics and the origin of mass beyond the SM boundary in high - energy physics by more powerful accelerators [23]. It is worth recalling that already in work the clarification of the origin of the observed world was linked with the nucleon mass [24]. To clarify this, it is necessary to understand the mechanism of breaking chiral symmetry (symmetry of the equations of motion due to the asymmetry of the Universe in QCD [24]. This author has shown that the breaking symmetry occurs at large distances of = 1 fermi = 10^{-15}m, and thus has no relation to high - energy experiments investigating small distances of 10^{-19}m [24, 25]. Incidentally, we note that after our work on strong interaction in the mass isotope effect, a whole of works appeared devoted to the search for new physics in the isotope effect of heavy chemical elements [26-32]. In other words, following us in those works, they are also trying to find a new type of boson interacting with a neutron and an electron.

This work complements the review with low - energy physics and the same time is a logical and experimental continuation of the work and is devoted to the search for new physics beyond the SM and the origin of mass [23, 25]. In particular, a nonlinear dependence of the coupling constant of strong interaction on the value of the neutron - electron binding energy was obtained for he first time. It has been shown that the maximum value of the neutron - electron binding energy in a number of crystals (LiD, C, Ge, ZnO) equal = 105 meV is in good agreement with Breit's theoretical estimate obtained in electrostatic model and equal 106.7 meV [20].

Experimental Results

The observation of the mas isotopic shift of the zero - phonon emission line of free excitons in low - temperature (2 K) luminescence spectra of LiH and LiD crystals was carried out on the setup described by us repeatedly [12, 33, 34]. For the sake of clarity, we will briefly add that he experimental setup consisted of a home - made helium cryostat and two monochromators perpendicular each other. The optical signal (light reflected from the crystal, its luminescence, or light scattered by crystal) was recorded by a highly sensitive photon counting system with the signal stored in the memory of a personal computer. Taking into account the high hygroscopicity of the crystals under study, we developed a technique for cleaving crystals in superfluid helium in a helium cryostat bath. The crystal surface prepared in this way it possible to obtain reliable and easily reproducible results. Numerous studies have shown that the fundamental absorption edge is described by direct electron transitions in the center of the Brillouin zone with the creation of large - radius excitons [34-36, 12].

The spectrum of free exciton photoluminescence of LiH crystals cleaved in superfluid helium (Figure 1) consists of a narrow zero - phonon emission line at the 4.950 eV and its broader phonon repititions which arise due to radiated annihilation of the free excitons with the production of one to five longitudinal optical (LO) phonons [12].

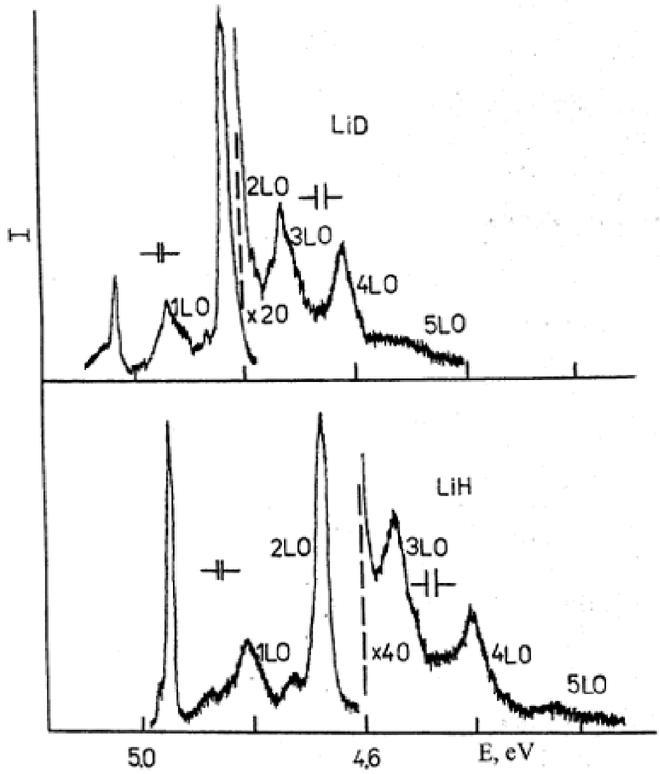

Figure 1: Photoluminescence spectra of free excitons at 2 K in LiH and LiD crystals cleaved in superfluid helium

The phononless emission line coincides in an almost resonant way with the reflection line of exciton ground state which is indication of the direct electron transition X_1-X_4 of the first Brillouin zone [33,35,36,37]. 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 phonons in the middle of Brillouin zone [38]. Photoluminescence spectrum of LiD crystals cleaved in superfluid helium is similar in its developed structure to the given spectrum of intrinsic photoluminescence of LiH crystals.

The isotopic short - wave shift of the zero - phonon emission line of free excitons in LiD crystals, as in the case of reflection spectra, is equal to 103 meV [35]. The second change in the luminescence spectrum of LiD crystals is associated with the phonon energy, which decreased to 104 meV. The emission spectrum of free excitons in mixed crystals LiH_xD_{1-x} (Figure 2) is in many ways similar the emission spectrum of free excitons in LiH and LiD crystals.

Changing the concentration of isotopes made it possible to grow (and reference quoted there) [35]. a whole range of LiHxD1-x mixed crystals. Measuring their reflection and luminescence spectra made it possible to find the energy of the zero - phonon emission line of free excitons of a whole series of crystals with different isotope concentration [34]. The results of these measurements made it possible to construct the dependence of the energy of the zero - phonon emission line of free excitons of deuterium concentration. The dependence of the lattice constant of LiHxD1-x mixed crystals on the isotope concentration, necessary for our work, according to the results of paper [38] is presented in Figure 3.

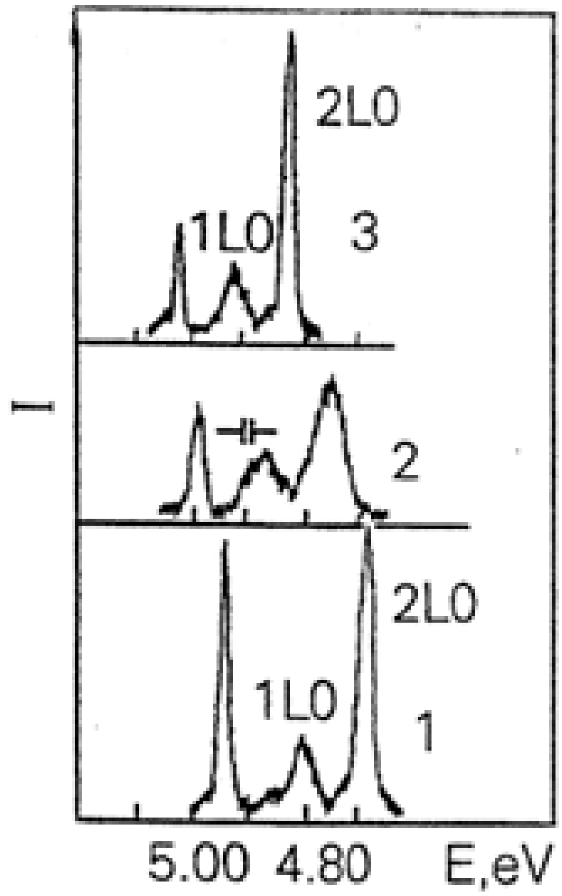

Figure 2: Photoluminescence spectra of free excitons in LiH (1), LiH_xD_{1-x} (2), and LiD (3) crystals cleaved in superfluid helium at 2 K. Spectrometer resolution is shown

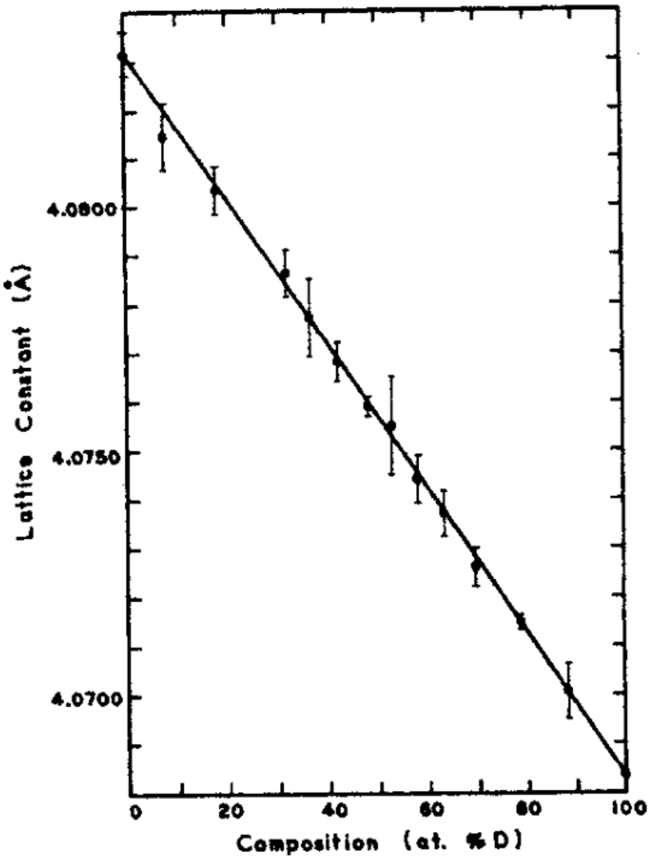

Figure 3: Lattice constant in the $^{7}Li(H, D)$ crystals plotted against the isotopic concentration (after [39]).

Vegard's law is well fulfilled - the linear dependence of the crystal lattice constant on the concentration of isotopes. The obtained experimental data from the present work made it possible to construct the dependence of the energy of strong interaction (the energy of the neutron - electron bond) on the distance between the proton and the neutron in the deuterium nucleus, taking into account the linear dependence on the lattice constant on the concentration of isotopes. The indicated dependence is depicted in Figure 4, where r_D and r_H are the radii of deuterium and hydrogen nuclei according CODATA [40].

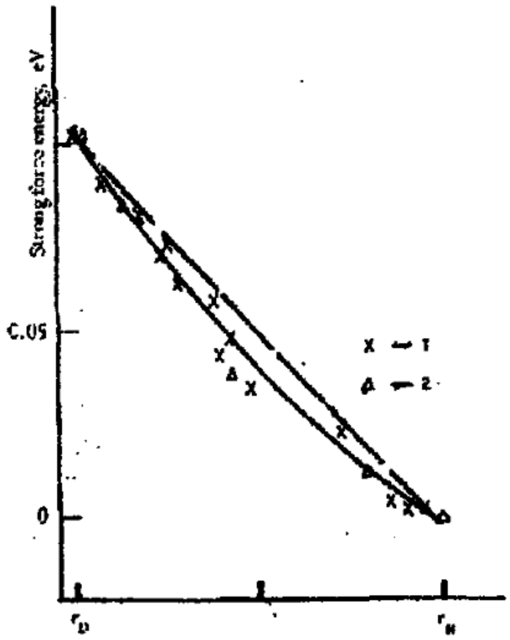

Figure 4: The long - range of the force of strong nuclear interaction dependence on the distance between nucleons in deuterium nucleus. The straight dashed line is linear dependence of the force dependence Fs in he virtual model. Points derived from reflection spectra indicated by crosses, and those from luminescence spectra by triangles.

Analysis of Results and their Discussion

It is well known from atomic spectroscopy that the isotopic shift of spectral lines arises as a result probably withdrawn of the shift relative to each other of the energy levels of atoms [13] belonging to different isotopes of the same chemical elements. This displacement is a result of the interaction of the electron shell with the nucleus. Therefore, the isotopic effect should manifest both the properties of the nucleus and the characteristic features of the electron shell. As noted earlier, the phenomenologically mass isotopic shift is caused by the correction of the kinetic energy of the atomic electrons by the motion of the nucleus and is described by formula (1). Quantum - mechanically, this interaction is described by the electron - phonon model [41]. The quantum mechanical solution to the task of electron - phonon interaction (in our case, neutron - electron interaction) is found taking into account the adiabatic approximation, which takes into account that mass of an electron is approximately 2000 times less than the mass of a nucleus [43]. The latter allows the use of perturbation theory.

The use of the adiabatic approximation leads to the appearance of non - adiabatic term [41], which is neglected due to its smallness (see formula 5 in [43]. It is precisely the neglect of the non - adiabatic term that allows us to reduce the given problem to two independent Schrödiger equations - electronic and nuclear. As shown in work, the electron equation does not depend on the mass of the nucleus, and therefore the energy eigenvalue is the same for different isotopes [43]. This conclusion, as well as the large of the isotopic shift energy, makes it necessary to search for new mechanism to describe the neutron - electron interaction, including subatomic physics [22].

The uniqueness of LiH_xD_{1-x} crystals, which made it possible to measure the energy of the zero - phonon emission line of free excitons in low - temperature luminescence spectra for different deuterium concentration opens up the possibility of quantitatively tracking the change in the strong interaction between a proton and a neutron depending in distance between them. Modern NP describes the stable state of atomic nuclei due to the residual strong interaction of quarks and gluons inside nucleons in the nucleus (analogous to the van der Waals interaction in atomic physics). Let us repeat that the quark - quark interaction carried by massless gluons inside nucleons is long - range, whereas the nucleon - nucleon interaction described by the Yukawa potential is short – range [2]. This is an old mystery that still has no consistent explanation in theoretical physics [4, 3]. The modern model of the atomic nucleus, according to Iwanenko and Heisenberg, consists of protons and neutrons, around which small - mass electrons revolve, the interaction of which with protons is described in a simple electrostatic model (see, for example [3, 20]]). Therefore, the well-known coefficient of a proton with an electron (equals to 13.6 eV) in the case of a sold it turns into a variable value of interband transitions E_g, is contained in any book on atomic physics [44,45]. The neutron, the second particle in the nucleus of an atom, has little studied properties. A demonstration of this is the lack of knowledge about the neutron - electron binding energy [46]. Since the LiH (without strong force in hydrogen nucleus) and LiD (with strong force in deuterium nucleus) crystals we used in our experiments differ by only one neutron, all other crystal - forming particle are indeed the same, and addition of a neutron to the hydrogen nucleus, according to Yukawa generates a strong interaction between the proton and neutron in the nucleus, which on the other hand, causes the observed isotopic shift of the zero - phonon emission line of free excitons in the low - temperature luminescence spectra of LiD crystals (see Figure 1). Considering that the value of E_g (the binding energy of a proton and an electron) is the same in LiH and LiD crystals, the increase in E_g in LiD is caused by the addition of a neutron to the hydrogen nucleus. In this case the difference between zero phonon emission lines in LiD and LiH crystals is equal to the neutron - electron binding energy of 0.103 eV. Similarly, in work it was shown that the neutron - electron binding energy in diamond is equal to 105 ± 3 meV, and for Ge and ZnO it is equal to 108 ± 5 meV and to 122 ± 10 meV, respectively [47]. Data for Ge and ZnO crystals are taken from review [34]. A good agreement is evident with the data of Breit (106.7 meV) obtained from the results of scattering of electrons (their length) more than half a century ago in the electrostatic model [20,46]. Naturally with an increase in the number of nucleons in the nucleus, it is necessary to take into account the field contribution, which was not done in our estimates [16]. Thus, spectroscopic measurements of the mass isotopic shift it possible for the first time to determine the neutron - electron binding energy. Using subatomic physics to interpret the results of measuring the strong interaction from the distance between the proton and neutron in the deuterium nucleus in LiD crystals allows us to estimate the energy of the boson responsible for the interaction of the neutron and electron and secondly to calculate the coupling constant of the strong interaction at different values of the binding energy. For an interaction radius equals to the Bohr radius a_0 = 0.52917706• 10^{-10}m, the Yukawa potential gives a boson mass value of = 3.7 keV*).

***)** Relativistic units (h = c = 1) were used to obtain this estimate.

This is very small energy value if we take into account that the binding energy of a proton and a neutron in deuterium nucleus is 2.224 MeV [3]. The found value of the neutron - electron bond energy, despite the smallness of its magnitude, nevertheless, as will be shown, determines a rather large of the strong interaction coupling constant.

Below, the dipole - dipole magnetic interaction model will be used to estimate the coupling constant of the strong interaction. 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 [48]).

The ground state wave function for the electron in the Hydrogen atom, including the spin part, is

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

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

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

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

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 (3) has a finite value for $r = 0$ so that the energy comes out from a contact-interaction (see, for example [3]). The magnetic dipole-dipole interaction can thus be treated as a perturbation. In first order perturbation theory:

$$E' = \int \psi_0{}^* H \psi_0 dV. \tag{5}$$

As mentioned, only the second term contributes giving:

$$E' = -\frac{2}{3} < \vec{m}_1.\vec{m}_2 > |\psi_0(0)|^2 = -\frac{2}{3}\frac{1}{\pi a_0{}^3} < \vec{m}_1.\vec{m}_2 >. \tag{6}$$

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

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

(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 (6), we obtain for the triple and singlet states in Hydrogen, the energies

$$E_t' = \frac{1}{3}\frac{e^2}{a_0^3 m_e M_p} g_p = 1.468510^{-6} eV$$

and

$$E_s' = -\frac{e^2}{a_0^3 m_e M_p} g_p = -4.405410^{-6} eV,$$

with a gap $\Delta E'$=5.87410^{-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 [40]) with the results

$$E_{3/2}' = 4.498010^{-7} eV$$

$$E_{1/2}' = -8.996010^{-7} eV$$

$$\Delta E_d' = E_{3/2}' - E_{1/2}' = 1.349410^{-6} eV.$$

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:

$$\Delta E = (E_s')_H - (E_{1/2}')_D = -3.505810^{-6} eV, \tag{7}$$

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

$$\alpha = e^2 \rightarrow (\alpha_s)eff = e.\ es. \tag{8}$$

The Bohr radius is thus modified:

$$a_s' = \frac{1}{e.e_s}\frac{1}{m_e}.$$

From (4), it is easy to obtain (see also [49])

$$(E_{1/2}')_D = -\frac{4}{3} g_d \frac{(\alpha_s')^4 m_e^2}{M_d}. \tag{9}$$

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. In high energy physics this value is usually equal to $\alpha_s(M_Z)$ = 0.1198

± 0/002 [50]. Note that regardless of the nature of the magnetic interaction (electromagnetic or color), the value of the strong interaction coupling constant is more than 20 times greater than the similar value of a distance of femtometers in NP and EPP. Using formula (9), we calculated the value αs as a function of the neutron - electron binding energy. The calculation results are presented in Figure 5.

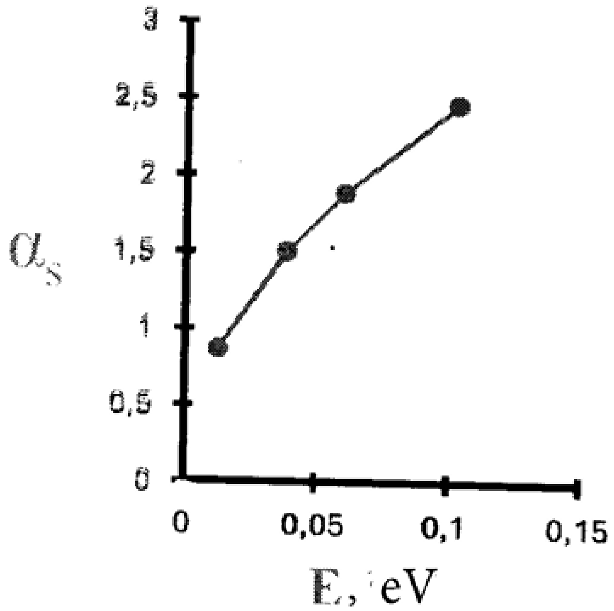

Figure 5: Dependence of the strong interaction coupling constant on the neutron - electron binding energy.

The observed nonlinear dependence coupling constant may be caused by the manifestation of a new unknown force of electromagnetic or color origin in the mass isotope effect. Let us also note that more than forty years ago, hints on the manifestation of a new force or higher terms of expansion of electromagnetic origin were expected by the author of the world - famous monograph on the isotopic shift in atomic spectra [16]. It should be added here that the authors of the already cited

works [26-32] are also busy searching for deviations from the King linearity in isotopic shift of heavy chemical elements in the hope that in this way they will be able to find either a new force or a new boson that carries out the neutron - electron interaction [16].

Conclusion

The observation of an isotopic shift (0.103 eV) of the zero - phonon emission line in the low - temperature luminescence spectra of LiH (without strong interaction in the hydrogen nucleus) and LiD (with strong interaction in the deuterium nucleus) was first and direct evidence of the long - range interaction of the Yukawa potential. The dependence of the proton - neutron interaction in the deuterium nucleus which was not available on accelerators hence it was first - time measured. The obtained nonlinear dependence of the strong interaction coupling constant on the neutron - electron binding energy is associated with the manifestation of a new force in the mass isotope effect, previously not observed. The need for further theoretical investigation of nucleon dynamics in nuclear physics is emphasized.

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