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Research Article

Non - Accelerator Measurement of the Long - Range Quark - Lepton Interaction in Solids

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Abstract

The measurements of the dependence of the energy of strong nuclear interaction on the distance between nucleons in nucleus were performed for the first time. By the adding one neutron to hydrogen nucleus we enable the strong interaction. The initial components of mixed crystals LiH_xD_{1-x} are LiH (no strong interaction in the hydrogen nucleus) and LiD (with strong interaction in the deuterium nucleus) crystals are dielectrics with cubic symmetry. The change of the concentration of deuterium in mixed crystals LiH_xD_{1-x} determines the change in the distance between nucleons, which is directly manifested in the position of the phononless free exciton emission line in the low - temperature luminescence spectrum. A series of such measurements made it possible to construct a function of the dependence of the energy of strong nuclear interaction on the distance between nucleons in the deuterium nucleus.

Keywords: Strong Interaction, Quarks, Gluons, Excitons, Phonons, Quantum electrodynamics, Quantum chromodynamics

1. Introduction

The hydrogen atom has a central position in the history of the 20 th - century physics. Simple atoms, like hydrogen, being essentially quantum electrodynamics (QED) systems, allow highly accurate theoretical predictions. QED is the first successful and still the most successful quantum field theory. After the discovery of the neutron in 1932 by Chadwick [1], there was no longer doubt that the building block of nuclei are proton and neutron (collectively called nucleons). The discovery of the neutron may be viewed as the birth of the strong nuclear interaction [2], [3]: 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. Theory strong nuclear interaction is the heart of quantum chromodynamics (QCD) which is part of the Standard Model (SM) [4], therefore the base exchange is the gluon which mediates the forces between quarks. Nucleus is a bound system of strongly interacting protons and neutrons (more generally baryons) holds atomic nuclei together and, in another context, binds quarks within hadrons. The baryons are bound states of the three quarks and mesons are composed of quark and antiquark (see, e.g. [5]).

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The phenomenological basis for strong nuclear interaction was laid down by Yukawa's paper [6]. Yukawa's potential has the form

$$\mathrm{V} = \mathrm{g}\mathrm{e}^{-\mathrm{kr}}/\mathrm{r}^{\mathrm{n}}, \tag{1}$$

for some n. Here the strength of the force is measured by the constant k (see, also [2]). The most important feature Yukawa's forces is that they have a small range ($\sim 10^{-15}$ m). The central dogma of atomic physics after Yukawa's paper that proton - electron attraction could be explained in terms of classical electrostatic theory, while the strong force effects were essentially new and inexplicable. The best theoretical guess is the Yukawa potential, but it is a static potential not dependent on velocities of the nucleons. A static force is not a complete one because it cannot explain the propagation of the nuclear interaction. Moreover, as was indicated above, a phenomenological Yukawa potential cannot be directly verified experimentally. We should note that nowadays in text books and elsewhere the separation of electromagnetic and strong interaction tacitly assumed. It is very strange up to present time we do not even know the strong force very well. And what is more we have some contradiction taking into account that the forces between quarks must be long - range, because the gluons have zero mass. But as was mentioned above the force between colorless hadrons is short - range, when the distance between hadrons is more than nuclear size [5]. We can see that the border of the nuclear size transforms long - range interaction in the short - range one. It is very old question which up to present time has not any theoretical explanation.

Recently we have shown that the origin of the isotope is due the strong nuclear interaction in solids [7] and presented it in a series of international conferences on high energy physics. The present paper describes the non - accelerator measurement of the long - range quark - lepton strong interaction and their dependence on the distance between nucleons in the deuterium nucleus. Using our experimental results we found the maximum value of the strong interaction coupling constant equal 2.680.

2. Experimental Results

The main experimental results were obtained on devices used already in the earlier investigations [9]–[12]. For clarity, we should mention here that the experimental method involves a home-made helium cryostat and two identical double-prism monochromators as well as a photoelectrical recording system with signal accumulation in the memory of a personal computer. For measuring the luminescence spectra the crystals were excited by the light from mercury (250 W) and deuterium (400 W) lamps.

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 spectroscopy) and through ab initio electronic structure simulation. Among other arguments, LiH and LiD are very interesting systems due to their extremely simple electronic and energy structure and to the large isotopic effects when the hydrogen ions are replaced by the deuterium ones.

The single crystals of LiH and LiD were grown from the melt by the modified method of Bridgeman - Stockbarger (see [11]–[13] 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 had a slightly blue – grey 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°C under $\sim$ 3 atm of hydrogen or deuterium, this color could be almost completely eliminated. Because of the high reactivity and high hygroscope of investigated crystals an efficient protection against the atmosphere was necessing. Taking into account this circumstance, we have developed special equipment which allows us to prepare samples with a clean surface, cleaving them in the bath of a helium cryostat with normal or superfluid liquid helium [9]. The samples with such surfaces allow us to perform measurements lasting 15 hours. An improved of LiH (LiD) as well as mixed

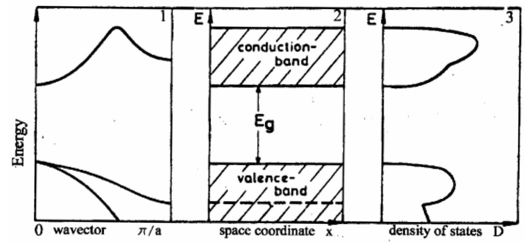

Figure 1. Various possibilities to present the band - structure of homogeneous undoped insulator (semiconductor). 1 - the dispersion relation, i.e. the energy E as a function of the wave vector k, 2 - the energy regions of allowed and forbidden states as function of a space coordinate x and 3 - the density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

crystals LiH_xD_{1-x} 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.

Before beginning a general discussion of long - range strong nuclear interaction, it is helpful to have an idea of electronic structure of bulk materials. As is well - known the nature of materials is determined by the interaction of their valence electrons with their charged nuclei and core electrons. This determines how elements react with each other, what structure the solid prefers, its optoelectronic properties and all other aspects of the material. The modern view of solid state physics is based on the presentation of elementary excitations, having mass, quasi-impulse, electrical charge and so on [14]. According to this presentation the elementary excitations of the non - metallic materials are electrons (holes), excitons (polaritons) and phonons. The theory discussed in modern text books (see, e.g. [15]) forms the basis for the modern theory of electrons in solid. It arises from the consideration of the periodicity of the crystal structure. This periodicity leads to the formation of energy bands (see Fig. 1). The importance of the electronic theory of solids as embodied in band theory is that it provides us with clear means of understanding how solids may be insulators, semiconductors, or metals. This depends upon whether or not it is Fermi surface. The existence of a Fermi surface produces metallic behavior, whereas at 0K, if the filled electron levels (bands in solids - see Fig. 1) are separated from vacant ones, we have insulating properties. The difference between a good conductor and a good insulator is striking. The electrical resistivity of a pure metal may be as low as 10^{10} ohm-cm at a temperature of 1 K, apart from the possibility of superconductivity. The resistivity of good insulator may as high as 10^{22} ohm-cm. The understand the difference between insulators and conductors, we shall use the band – gap picture (Fig. 1). The possibility of band gap is the most important property of solids.

Free exciton luminescence is observed when LiH (LiD) crystals are excited in the midst of the fundamental absorption. The spectrum of free exciton photoluminescence of LiH crystals cleaved in 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 radiated annihilation of free excitons with the production of one to five longitudinal optical (LO) phonons (see Fig. 1 in Reference [9]).

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 [1]. 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.

The isotopic shift of the zero - phonon emission line of LiH crystals equals 103 meV. As we can see from Fig. 1 (Reference 9) the photoluminescence spectrum of LiD crystals is largely similar to the spectrum of intrinsic

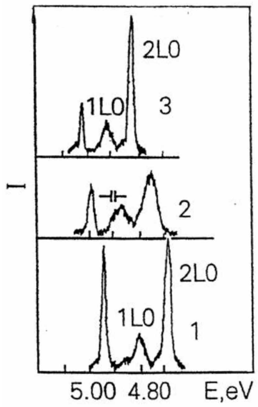

Figure 2. Photoluminiscence spectra of free excitons in LiH (1), LiH_xD_{1-x} (2) and LiD (3) crystals cleaved in superfluid helium at 2 K. Spectrometer resolution is shown.

luminescence of LiH crystals (see, also Fig. 2). 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 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. 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) [15].

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. 2), like in the pure LiH and LiD crystals. As before [12], [15], 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 scarficing generality, Fig. 2 shows the lines of two replicas. Usually up to five LO repetitions are observed in the luminescence spectrum as described in detail in [1]. In Fig. 2 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 measurements of the low temperature of reflection [15] and luminescence spectra of the whole series of mixed crystals is permitted to obtain the dependence of the interband transition (the long - range force dependence of strong nuclear interaction on the distance between nucleons in deuterium nucleus) energy on the deuterium concentration (Fig. 3). This dependence has a nonlinear character. As can be seen from Fig. 3, VCA method (the straight dashed line) cannot describe observed experimental results.

Comparison the experimental results on the luminescence (reflection) and light scattering [19] in the crystals which differ by a term of one neutron only we may conclude:

1. At the adding one neutron (using LiD crystals instead LiH ones) is involved the increase exciton energy up to 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.
3. In the isotope effect, the energy of acoustic phonons does not depend on the replacement of H by D [18], which is proved by the identical structure of the light scattering spectra [19]. Along with this, a small change in the

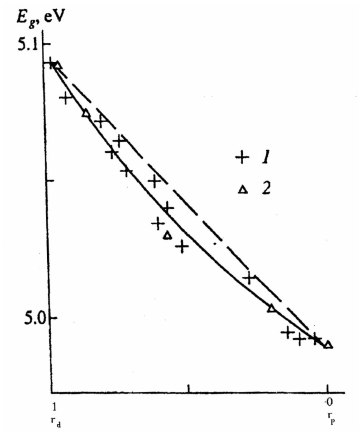

Figure 3. The force dependence of strong nuclear interaction on the distance between nucleons in deuterium nucleus. The straight dashed line is the linear dependence of the force dependence F_s=f(x) in the virtual model. The solid line corresponds to calculation using the polynom of second degree $F_s = f(r_d)$. Points derived from the reflection spectra indicated by crosses, and those from luminescence spectra by triangles.

energy of optical (LO) phonons (36 meV) observed in the luminescence and light scattering spectra indicates a non - electron - phonon renormalization mechanism of the energy of zero - phonon emission line of free excitons in LiD crystals.

3. Discussion

Traditionally nuclear - electron interaction in our case neutron - electron interaction taking into account the solving of Schrödinger equation using a model of Born - Oppenheimer (adiabatic) approximation [16]. Since electrons are much faster and lighter than the nuclei by a factor nearly 2000 the electron charge can quickly rearrange itself in response to the slower motion of the nuclei, and this is the essence of the Born - Oppenheimer approximation. This approximation results the omission of certain small terms which result from the transformation. As was shown in [18] the eigenvalue (energy) of the electronic Schrödinger equation (equation 6 in [17]) depends on the nuclear charges through the Coulomb potential, but it doesn't include any references to nuclear mass and it is the same for the different isotopes (see also [16], [18]). The independent of the potential energy (the eigenvalue of the Schrödinger equation) is the essence adiabatic approximation. However, we must repeat, that the Born - Oppenheimer approximation is the standard ansatz to the description of the interaction between electrons and nuclei in solids (see, however below). Now we should take into account a small contribution to isotopic shift through reduced electron mass $\mu = ((m_e M_{Nucl})/(m_e + M_{Nucl}))$ so far as M_{Nucl} is different for the hydrogen and deuterium nucleus. In this case the contribution equals $\Delta E \simeq 6$ meV. Contribution to isotope shift of the zero - phonon line in luminescence spectra of LiD crystals as well as Lamb shift and specific Coulomb potential approximately equal 1, and 1 meV, respectively. This value is less than isotope shift in our experiments, by two orders or more. The last result is forcing us to search for new models and mechanisms of nuclear - electron interaction including results of subatomic physics, e.g. hadron - lepton interaction.

The formulation of the model explaining the non - accelerator experimental results on the mass isotope effect requires a more careful analysis of the origin of the four fundamental forces. It is reasonable to recall that more than three decades ago, Barut [20] hypothesized that all fundamental forces have an electromagnetic nature (see, also [21]). Out of four known interactions, three are described by SM - the electromagnetic, weak and strong ones [4, 5, 22]. The first two of them have a common electroweak gauge interaction behind them. The strong interaction in SM is described by the QCD, a theory with the gauge group SU(3)C. The effective coupling constant of this theory grows when the energy decreased. As a result, particles which feel this interaction cannot exist as free states and appear only in the form of bound states called hadrons (see, also [22]). Most of modern methods of quantum field theory work at small values of coupling constant, α_s, [23], that is, for QCD, at high energies. Quarks and leptons, the so - called SM matter fields, are described by fermionic fields. Quarks take part in strong interactions and compose observable bound state hadrons. Both quarks and leptons participate in the electroweak interaction. The matter fields constitute three generation: particles from different generation interact identically but have different masses (see, e.g. [5], [22]). The gauge bosons, which are carriers of interactions are massless for unbroken gauge groups $U(1)_{EM}$ (electromagnetism - photons) and SU(3)C (QCD - gluons), masses of $W^{\pm}$ and Z^0 bosons are determined by the mechanism of electroweak symmetry breaking. It should note that the forces between the quarks must be long rang, because the gluons have zero mass. This does not imply that forces between hadrons are also long range, because hadrons have zero color charges overall. The forces between the colorless hadrons are the residues of the strong forces between their quark constituents, and cancel when the hadrons are far apart.

The diagram of Fig. 4 is drawn for the case of single – gluon exchange, but taking into account that strong constant coupling $\alpha_s \sim 1$, multiple exchanges, involving terms α_s^2, ${\alpha_s}^2, \ldots$ must also be very probable. However, it turns out that for violent 'close' collisions at very high q^2, $\alpha_s \ll 1$ and single - gluon exchange is a good approximation, while at low q^2 or, equivalently, larger distances, the coupling becomes very large and the theory is incalculable (see also [2]–[21]). This large - distance behavior is presumably linked with of confinement of quarks and gluons inside hadrons. Since gluons are massless, one might expect the static QCD potential to have a similar 1/r form to that in QED. In fact the quark - antiquark potential is often taken to be of the form [5]

$$V_s = -(4/3)((\alpha_s)/r) + kr \tag{2}$$

where the first term, dominating at small r, arises from single - gluon exchange. It is similar to the Coulomb potential between two unit charges of

$$V_{em} = -(\alpha/r) \tag{3}$$

The factor 4/3 in (2) is plausible in view of the fact that there eight color gluon states, to be averaged over three quark colors, giving factor 8/3 as compared with QED (one 'color' of photon and one fermion charge). This has to divide by 2 because, for historical reasons [22], a factor 2 enters into definition of α_s in terms of the square of the strong color charge. However, at larger distances the second term in (2) is dominant and is responsible for quark confinement. The value of k is about 0.86 $GeVfm^{-1}$. In equation (2) the attractive force at large r is dV/dr = k = 0.85 $GeVfm^{-1}$ [4]. The estimation of the value of k = 13.9 tons weight — a great deal for those tiny quarks, each weighing less than 10^{-24} g. Because gluons carry a color charge (unlike photons which are uncharged) there is a strong gluon - gluon interaction.

Returning to our non - accelerator experimental results, we should underline that in this paper we measure the low - temperature luminescence spectrum of LiH_xD_{1-x} mixed crystals. We should repeat that LiH crystals are without

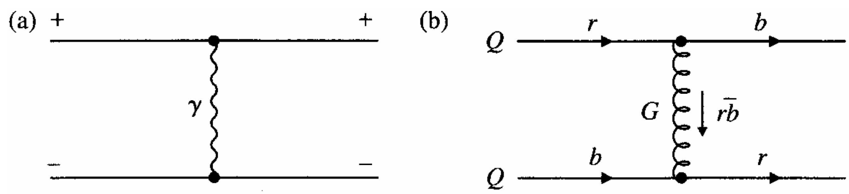

Figure 4. Comparison of the Feynman diagrams of electromagnetic (a) and strong (b) interactions. The electromagnetic interaction in (a) involves two types of electric charge, (+) and (−) is mediated by an uncharged photon. In (b) the strong interquark force involves six types of color charge. The diagram depicts the interaction of a red quark with a blue quark via the exchange of a red - antiblue gluon.

strong interaction in hydrogen nucleus and LiD crystals are with strong interaction in deuterium nucleus. When we add one neutron in the hydrogen nucleus, we artificial activated of the strong interaction. As far as the gravitation, electromagnetic and weak interactions are the same in both former crystals (LiH and LiD), it only emerges the strong interaction (see, also [9], [21]). Therefore a logical and historical [25], [26] conclusion is made in paper [8], [12] that the renormalization of the energy of electromagnetic excitations (isotopic shift equals 0.103 eV [15]) is carried out by strong nuclear interaction. The short range character of the strong interaction of nucleons in SM does not possess direct mechanism of the elementary excitation (electrons, excitons, phonons) energy renormalization, which was observed in our low temperature experiments. Second reason that the interpretation of our experimental results is very difficult task because they are first demonstration of the violation of the strong conclusion in nuclear and particles physics that the strong nuclear force does not act on the colorless leptons (see, e.g. [22], [23]). Moreover in paper [27] we read “We do not know the origin of the strong nuclear force very well”. It should be added that before present work there were no measurements of the dependence of the energy (force) strong nuclear interaction on the distance between nucleons in the nucleus. In our tentative interpretation (the electromagnetic origin) we should suppose that the potential of strong interaction has the next form:

$$\mathrm{V(r)} = -((\mathrm{Z}\alpha)/(\mathrm{r})) + (1 + \mathrm{e}^{\mathrm{m'r}}\chi^2) \equiv \mathrm{V_{Coulomb}} + \delta\mathrm{V(r)}, \tag{4}$$

where Z is the charge of the massive central particle which causes the potential and α is the fine structure constant. Here is the second term term is Yukawa’s short - range potential, and the first term which has a long - range character of interaction and depends on the distance between nucleons in deuterium nucleus. The most intensively studied atomic scale is at a few values of the Bohr radius, $\mathrm{a_0} \simeq 0.53 \times 10^{-10}$ m. For the Yukawa radius equal to $\mathrm{a_0}$, the related mass m’ of the intermediate new kind particle (boson) is 3.5 keV which interact with hadron (neutron) and lepton (electron) (for details see [21] and references therein). The origin of the first term in equation (4) is due the magnetic - like long - range interaction (possibly not point - like neutron and electron [28], [29]). This assumption is in accordance with very large value magnetic moment of neutrons (see, also [2], [3], [30]). Moreover, as we can see from results of Fig. 3 the force dependence of strong nuclear interaction on the distance between nucleons in deuterium nucleus has a nonlinear character. With increase the distance between nucleons the force of strong nuclear interaction is increased. We should stress that this is the first observation in experiments the force dependence of strong nuclear interaction on the distance between nucleons in nucleus. A possible interpretation is to assume that in addition to the 8 gluons predicted by QCD SU(3)C group there is a ninth gluon color singlet [22] as photon and may interacts with colorless hadrons and leptons.

$$\mathrm{g_9} = (1/(\sqrt{}3))(\mathrm{r\underline{r}} + \mathrm{g\underline{g}} + \mathrm{b\underline{b}}), \tag{5}$$

where $\underline{\mathrm{r}}$, $\underline{\mathrm{g}}$, $\underline{\mathrm{b}}$ are antiquarks. This massless photon like gluon may be strongly interacts between nucleons (neutrons) and leptons (electrons) [22]. So, the first point to realize is that despite the numerous textbook statements, all leptons are feeling the strong nuclear interactions. This strong conclusion is a direct consequence of our non - accelerator experimental results - the origin of the mechanism of interaction between hadrons and leptons is a task for future theoretical and experimental investigations.

4. Conclusion

The main feature of the present work is that measurements of the dependence of the energy of strong nuclear interaction on the distance between nucleons in a nucleus were performed for the first time, and these results allow us to find the maximum possible value of $\alpha_{\mathrm{s}} = 2.4680$. Our non - accelerator results opens new avenue in the investigation of the propagation the force of strong nuclear interaction in the wide value range by means the condensed matter alike traditional accelerator methods. These results may shed light on a number of fundamental puzzles in modern physics, particularly on the unification of forces taken into account long - range strong nuclear force. Experimental observation of the renormalization of the elementary excitation energy of solids by the strong nuclear interaction stimulates its count in the process of description of the elementary excitation dynamics in quantum electrodynamics. Besides, we should highlight that such important information has been obtained via rather simple and inexpensive experimental physics equipment.

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