Cooper-Pair Breaking

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Abstract: Theoretical results obtained in this paper are perfectly consistent with the experimental data presented by Mannila, et al. (2021). We described the origin of three new formulae for the normalized number density of quasiparticles, relaxation times of bursts, and statistical distribution of the broken Cooper pairs per burst. We show that the Cooper-pair breaking is due to the nuclear weak interactions of the spacetime condensates created in the core of nucleons.

1. Introduction

Superconductors free from quasiparticles (QPs) that force decays of the Cooper pairs (CPs) into electrons, are very important in superconducting quantum computing. It is assumed that QPs corrupt the superposition. Just the Cooper-pair breaking decreases the coherence times of superconducting qubits.

Here we show that shielding against the ionizing radiation background (IRB) is not enough to eliminate QPs from superconductors built of chemical elements because the nuclear weak interactions, which are responsible for creations of QPs, are ubiquitous in all physical conditions.

The global features of superconductivity based on the Scale-Symmetric Theory (SST) we described in [1]. There appear the three phonon fields. Here by applying the internal dynamics of the core of nucleons described in SST [2], [1], we show that the Cooper-pair breaking is the result of the nuclear weak interactions of the spacetime condensates created in the core of protons and neutrons.

But this paper is written in such a way as not to refer to the SST. All applied here quantities are also calculated in SST with very high accuracy [2]. To make our paper clearer, our main results obtained in this paper are marked in red and our new formulae in blue.

Our basic assumption is that the neutral pion π^o (π^o = 134.9768(5) **MeV** [3]) consists of two entangled spin-1 fundamental gluon loops/circles (FGLs) with antiparallel spins and size of ~1 **fm**. It leads to conclusion that energy of the FGL is $m_{FGL} \approx 67.5$ **MeV**. Two such FGLs (they are responsible for the nuclear strong interactions and coupling constant at low energy is $\alpha_s = 1$ [3]) can collapse to two a spin-0 spacetime condensates Y that are responsible for the nuclear weak interactions – there is a transition from circular oscillations ($\lambda = 2\pi r$) to radial oscillations ($\lambda^* = r$) so mass of Y should be 2π times higher than the energy of FGL: $Y = 2\pi\, m_{FGL} \approx 424$ **MeV**.

We define the coupling constants as follows

$$\alpha_i = G_i M_i m_i /(c \hbar) , \quad (1)$$

where G_i, c and $\hbar$ are the constant values, M_i is mass of a source, and m_i is mass of a carrier of interactions.

Assume that for the nuclear strong and weak interactions, there are equators for which is

$$G_i M_i = c^2 r_i , \quad (2)$$

so we have

$$\alpha_i \sim r_i m_i . \quad (3)$$

For a loop is r_i = const. so we obtain

$$\alpha_i \sim m_i . \quad (4)$$

The nuclear weak interactions are responsible for the beta decay of neutrons so from (4) we have that value of the coupling constant for such interactions is

$$\alpha_{w(p)} = \alpha_s (n - p) / m_{FGL} \approx 0.019 , \quad (5)$$

where $n = 939.565413(6)$ **MeV** and $p = 938.272081(6)$ **MeV** [3].

For the spin-0 spacetime condensates we have $M_i = m_i$ so from (1) is

$$\alpha_i \sim M_i^2 . \quad (6)$$

Assume that the weak mass of electron interacting with proton is

$$m_{w(e)} = \alpha_{w(p)} m_e . \quad (7)$$

From (5), (6) and (7) we can estimate the coupling constant for the weak interactions of electrons

$$\alpha_{w(e)} = \alpha_{w(p)} [\alpha_{w(p)} m_e / (n - p)]^2 = \alpha_{w(p)}^3 [m_e / (n - p)]^2 \approx 1 \cdot 10^{-6} . \quad (8)$$

We use also following quantities.

*Fine-structure constant: $\alpha_{em} = 1 / 137.035999084(21)$ [3].

*Mass of electron: $m_e = 0.5109989461(31)$ **MeV** [3].

*Bare mass of electron: $m_{e,bare} = m_e / [1 + 0.00115965218091(26)] \approx 0.510407$ **MeV** [3].

*Mass of muon: $\mu^{\pm} = 105.6583745(24)$ **MeV** [3].

2. Number density of quasiparticles normalized by the Cooper-pairs density

Number density, n_i, is inversely proportional to energy of field components E_i (heavier particles are fewer)

$$n_i \sim 1 / E_i \quad (9)$$

We assume that energies of phonons are the electroweak masses of the oscillation masses, radiation masses, and masses of the electron-positron pairs – the three different masses in the electron-positron pair are denoted by M_1 (when interactions occur one after the other, the total coupling constant is the product of the coupling constants)

$$E_{Phonon} = M_1\, \alpha_{w(p)}\, \alpha_{em}\, \alpha_{w(e)} \qquad (10)$$

so for the number density of the Cooper-pairs, n_{CPs}, we have

$$n_{CPs} \sim 1 / (M_1\, \alpha_{w(p)}\, \alpha_{em}\, \alpha_{w(e)})\,. \qquad (11)$$

We assume that for quasiparticles (QPs) is (emphasize that energy of quasiparticle must be much higher than energy of the composite phonons)

$$n_{QPs} \sim 1 / (M_2\, \alpha_{w(p)})\,, \qquad (12)$$

i.e. we assume that they are created due to the nuclear weak interactions.

Our definition for number density of quasiparticles normalized by the Cooper-pairs density looks as follows

$$x_{QPs} = n_{QPs} / n_{CPs} = M_1\, \alpha_{em}\, \alpha_{w(e)} / M_2\,. \qquad (13)$$

3. Normalized number density of quasiparticles from the ionizing radiation background (IRB)

Due to the ionizing radiation background, for $M_2 = M_1$, we have

$$x_{QPs,IRB} = \alpha_{em}\, \alpha_{w(e)} \approx 7 \cdot 10^{-9}\,. \qquad (14)$$

It is consistent with experimental data [4]. It suggests that the Cooper-pair breaking are indeed due to the creations of quasiparticles in the nuclear weak interactions – their energy is $M_2 \alpha_{w(p)}$.

4. Most important transitions in superconductors

Assume that following transitions are most important in nucleons ($Y \approx 4\mu^{\pm}$)

$$m_{FGL} \rightarrow 2\pi\, m_{FGL} \rightarrow Y \rightarrow 4\,\mu^{\pm} \rightarrow k\, m_{e,bare}\ (k \approx 828)\,, \qquad (15)$$

and there is involved at least one electron-positron pair $2m_e$.

5. Relaxation times of bursts

From formula $E_i\, \tau_i$ = const., where τ_i is a lifetime of a virtual energy E_i, we have

$$f_{minimum} = \tau_{Cooper,mean} / \tau_{burst,1} = Y / (2\, m_e) \approx 415\,. \qquad (16)$$

where $\tau_{Cooper,mean}$ is the mean period free from quasiparticles, and $\tau_{burst,1}$ is the lifetime for 1-quasiparticle burst. For $\tau_{Cooper,mean} \approx 0.4$ **s** [5], from (16) the relaxation time for 1-quasiparticle burst is $\tau_{burst,1} \approx 960$ **μs**.

For two quasiparticles we have $Y \rightarrow 2\ Y$ so from (16) we have $\tau_{burst,2} \approx 480\ \mathbf{\mu s}$.
For three quasiparticles we have $Y \rightarrow 3\ Y$ so from (16) we have $\tau_{burst,3} \approx 320\ \mathbf{\mu s}$.
For four quasiparticles we have $Y \rightarrow 4\ Y$ so from (16) we have $\tau_{burst,4} \approx 240\ \mathbf{\mu s}$.
Our theoretical results are close to experimental data (see Fig.3a in [5]). It validates the transitions presented in (15).

Our formula for relaxation times of bursts created by quasiparticles looks as follows

$$\tau_{burst,i} \approx 0.4\ [s] \ / \ (f_{minimum}\ N_{QP})\ , \qquad (17)$$

where N_{QP} denotes number of quasiparticles in a burst. For $N_{QP} = 0$ we obtain $\tau_{burst,i} \rightarrow \infty$ – it is consistent with [5] (see Fig.3a in [5]). For $4 \leq N_{QP} \leq 9$, we obtain $\tau_{burst,4\text{--}9} \approx 210\ \mathbf{\mu s}$ (see formula (25) in this paper).

6. Lower limit for normalized number density of quasiparticles

The transitions from the circular vibrations to radial vibrations (i.e. $M_1 / M_2 = 1 / (2\pi)$) cause that the lower limit for number density of quasiparticles normalized by the Cooper-pair density is

$$x_{QPs,lower} = \alpha_{em}\ \alpha_{w(e)} \ / \ (2\ \pi) \approx 1 \cdot 10^{-9}\ . \qquad (18)$$

It is consistent with experimental data [6]. Equality of the experimental result and theoretical result obtained in (18) validates the $m_{FGL} \rightarrow 2\pi\ m_{FGL}$ transitions in the core of baryons.

But for two interacting FGLs, the transition $\pi^o \rightarrow Y$ gives

$$x_{QPs,pion\text{-}Y} = \pi^o\ \alpha_{em}\ \alpha_{w(e)} \ / \ Y \approx 2 \cdot 10^{-9}\ . \qquad (19)$$

It is consistent with [5]. It suggests that instead the transitions $m_{FGL} \rightarrow 2\pi\ m_{FGL}$, there dominated the transitions $\pi^o \rightarrow Y$.

7. Function for statistical distribution of the broken Cooper pairs

The statistical distribution of the broken Cooper pairs, n^*, is very well described by following our function (it is not the exponential function in [5])

$$N_{events,n^*} = \delta\ (2^{10 - n^*})^{\beta}\ , \qquad (20)$$

where δ and $\beta = 3/2$ are some factors. Fortunately, for data in [5], there is $\delta = 1$! So we have

$n^* = 1$ gives $N_{events,n^*=1} \approx 1.159 \cdot 10^4$,
$n^* = 2$ gives $N_{events,n^*=2} = 4096$,
$n^* = 3$ gives $N_{events,n^*=3} \approx 1448$,
$n^* = 4$ gives $N_{events,n^*=4} = 512$,
$n^* = 5$ gives $N_{events,n^*=5} \approx 181$,
$n^* = 6$ gives $N_{events,n^*=6} = 64$,
$n^* = 7$ gives $N_{events,n^*=7} \approx 22.6$,
$n^* = 8$ gives $N_{events,n^*=8} = 8$,

$n^* = 9$ gives $N_{events,n^*=9} \approx 2.82$,
$n^* = 10$ gives $N_{events,n^*=10} = 1$. (21)

The SST results that follow from (20) are in perfect agreement with experimental data (see Fig.2b in [5]). It suggests that the Titius-Bode (TB) numbers are very important

$$2^{10-n^*} = 512, 256, 128, 64, 32, 16, 8, 4, 2, 1 \text{ (the 10 TB numbers)} . \tag{22}$$

The TB numbers very frequently appear in SST [2].

8. The origin of the function for statistical distribution of the broken Cooper pairs

Formula (20) requires further research. What is the origin of the parameter $\beta = 3/2$?

We can assume that the decays of the Y spacetime condensate into the entangled electrons-positron pairs (see (15)) can be realized via two phenomena, i.e. by creating a string or a loop both composed of the electron-positron pairs. The jet-like expansion of the string has one degree of freedom while the disc-like expansion of the loop has two degrees of freedom.

For a short time, the virtual spacetime condensates Y look like a mini black hole with a jet and an accretion disc.

For the same mass of the jet and disc, their abundances should be the same, i.e. 50% - it leads to conclusion that the decaying and expanding Y or other spacetime condensates have $\beta = 3/2$ degrees of freedom and such is the origin of the parameter β in formula (20).

What is the origin of the TB numbers?

The TB numbers, 2^{10-n^*}, follow from the successive symmetrical decays of the Y – the last decay leads to $512 = 2^{10-1}$ entangled electrons and positrons (**so also electrons in Cooper pairs**; notice that there is one quasiparticle per each electron from the broken Cooper pairs) because their number cannot be bigger than 828 that follows from (15). The ratio $512/828 = 0.618$ is very close to the golden ratio. Jets and discs with fewer pairs are more numerous.

We can normalize the parameter δ to have opportunity to compare different experimental results. If in an experiment, there appear $N^*_{events,n^*=1}$ bursts with one broken Cooper pair then we have

$$\delta = 2^{9\beta} / N^*_{events,n^*=1} . \tag{23}$$

We can see that in [5] is $N^*_{events,n^*=1} \approx 2^{9\beta}$ so $\delta = 1$.

Our normalized function for the statistical distribution of the broken Cooper pairs looks as follows

$$N_{Norma,events,n^*} = 2^{13.5} \left(2^{10-n^*}\right)^{3/2} / N^*_{events,n^*=1} , \tag{24}$$

Now by applying (21) and (17), we can calculate the mean relaxation time of bursts for $4 \leq N_{QP} \leq 9$

$$\tau_{burst,4\text{--}9,mean} \approx$$

$$\approx 0.4\ [s] / [415\ (4\cdot512+5\cdot181+6\cdot64+7\cdot22.6+8\cdot8+9\cdot2.82) / (512+181+64+22.6+8+2.82)] =$$

$$= 0.4\ [s] / [415\ (3584.58 / 790.42)] \approx 210\ \mu s\ . \qquad (25)$$

This SST theoretical result is consistent with the experimental result presented in [5] (see Fig.3a in [5]).

Notice also that there is valid following relationship

$$N_{events,n*=1} / N_{events,n*=10} \approx 1.16\cdot10^4\ . \qquad (26)$$

9. Summary

Here we showed that it is impossible to dampen to zero the real and virtual processes in the core of baryons so we cannot eliminate the Cooper-pair breaking in superconductors. There is the lower limit for the number density of quasiparticles which are responsible for the pair-breaking.

The theoretical results obtained in this paper, i.e. the normalized number density of quasiparticles, relaxation times of bursts, and statistical distribution of the broken Cooper pairs per burst, are consistent with experimental results presented in [5].

Emphasize that presented here model is very simple.

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