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WAVE FUNCTION OF INDUCED SUPERCONDUCTIVITY: THE PROXIMITY EFFECT

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Abstract - *We have obtained the wave function for superconductivity induced in the normal metal and the superconducting substrates at ambient temperatures, using the BCS formalism and the proximity effect. The wave function obtained was subjected to Fourier expansion so as to have proper description of its propagation in the normal metal. Inter-atomic distance values of pure metals like lead, europium and iron and superconducting materials such as Mercury based cuprate (Hg1223), Thallium based cuprate (TI1220) and Iron based material (LnFeASO$_{0.6}$) were used to estimate their extrapolation length b . Lead, europium and iron metals showed extrapolation lengths of 0.00012 Å , 0.00013 Å and 0.00015 Å in that order. Mercury, Thallium and Iron based material attained extrapolation length of 0.00046 A ,0.00054 A and 0.0006 Å respectively. Variation of both Fourier integer n and inter-atomic distance a were found to have an effect on b . Since proximity effect is much related to thermoelectric phenomena, the concept will strengthen the formation of Josephson junction applied in the construction of Superconducting Quantum Interference Devices (SQUIDs).*

***Key Words*:** Wave function, Induced Superconductor,Proximity Effect.

1.INTRODUCTION

Proximity effect can be observed in all superconductors and it is a phenomenon that was discovered in 1960s and occurs if a normal metal (N) is into perfect contact with a superconductor (S). In this case it is noted that cooper pairs are able to leak from the superconductor into the normal metal, this alters the properties of the metal. When cooper pairs make their way into the normal metal, they propagate coherently over a certain distance which depend on the diffusive constant, energy of electron state in relation to the Fermi energy and face coherent length in the normal metal (Ying, Mondaini , Sun, Paiva, Fye & Scalettar , 2014). The density state of the normal metal becomes modified by the penetrated cooper pairs into it over a distance from the S-N interface; the distance is similar to that of electron state coherent propagation distance. Such modifications have so far been incompletely resolved by tunneling concepts. In the past few years, notable progress has been made in the controlled expansion of atomically pure material kept in an ultrahigh vacuum state. This has been simplified to test the proximity effect with high energy resolution. Proximity effect is not only restricted to a S-N systems, in case of a superconductor S_1, having a critical temperature T_{C1} and an Δ_1 Is made to be in contact with another superconductor S_2 with a critical temperature T_{C2} and an energy gap Δ_2, and if one of the critical temperature is lower than the other say $T_{C2} < T_{C1}$ and varying energy gaps say $\Delta_2 < \Delta_1$, modifications of the density of states near the junction in both superconductors is expected (Yamase, Eberlei, and Metzner, 2016). The modifications are noticeable more at low enough temperatures . In the temperature $T_{C2} < T < T_{C1}$, there is possibility of proximity effect inducing order parameter into a superconductor S_2 due to a non zero attractive pairing interaction existing in S_2. This kind of mechanism results into proximity induced interface superconductivity. Due to the modification of the density states of the normal metal and entry of cooper pairs into it, this research was therefore done analyze characteristics of order parameter into the normal metal. Studies have shown that one of the current methods of inducing superconductivity into other materials is through proximity effect. In proximity effect a material is brought into contact with a superconductor. This new techniques could also be used to improve efficiency of a giver superconducting materials and providing a proposal for modern ways of advancing efficiency of a superconductor. This method provides a new technique to manufacture superconductors that can operate at higher temperatures (Rainer, 2016).

2.METHODOLOGY

Both Theories of Proximity effect at S-N junction and BCS theory of superconductivity were used in this research.The theory ofProximity effect states that provided bothsuperconductor and the normal metal are in perfect contact Cooper pairs can leak from S to N, modifying the properties of the metal (Clerk, 1968). The BCS theory describes superconductivity as a microscopic effect that emerges due to condensation of cooper pairs into boson like states at temperature below transition temperature. The effective net attraction between the normally repulsive electrons produces a pair binding energy in the order of milli-electron volts, enough to keep them paired at extremely low temperatures. Order parameter and superconducting electron density were given through phase stiffness as provided in the literature by Andrei, (2004). In considering the S- N system at temperature less than transition temperature, order parameter as a function of ground state superconducting electrons density was identified as expressed by Andrei, (2004).The ground state superconducting electrons density was then substituted into the order parameter expression to make the order parameter a function of extrapolation length b and inter-atomic distance a . Both a and b areprovided by Ginzburg Landau Coherence Length $\varsigma_{GL}(0)$ which is a parameter in the superconducting electrons density expression. The order parameter was subjected to Fourier analysis for expansion to enable description of the order parameter wave as it propagates into the normal metal.

3.THEORETICAL FORMULATION

The effective coherence length of pure metals (where electron mean path e_N is much larger than the effective coherence length ς_N) is given as (Annica *et. al*, 2008)

$$\varsigma_N = \frac{v_{F,n}}{2\pi K_B T} \quad ......(1.1)$$

Where $v_{F.n}$ Fermi velocity is found in the normal metal and K_B is Boltzmann Constant. In dirty limit when e_N is much less than the effective coherence length of the normal metal N. Order parameter is a measure of the energy gap in the spectrum and it is measured from some reference point in the energy level. The behavior of order parameter $\psi(r)$ near the junction between the superconductor S and normal metal N at $x>0, x<0$ and when $T << T_c$ is expressedin fig. 4.1.

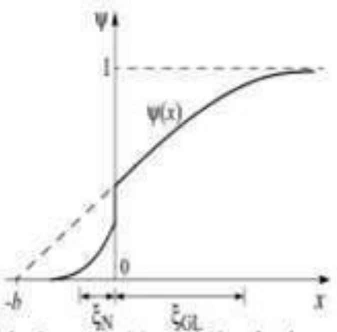


Figure 4.1. Order Operator $\psi(r)$ near the interface between superconductor $(x>0)$ and a normal metal $(x<0)$ at $(T << T_c$

Source: Andrei, (2004)

The ability of the superconductor to carry super current (phase stiffness or energy scale) is given by (Andrei, 2004)

$$\eta_{ph} = \frac{AK_B{}^2 n_S(0)\varsigma_{GL}(0)}{} \quad .... (1.2)$$

Where , η_{ph} is the phase stiffness, m^* is the effective mass of charge carrier, A is the dimensionless number of order 1 which depends on the details of short distance physics, $\varsigma_{GL}(0)$ is zero temperature Ginzburg Landau Coherence Length, is reduced planck's constant and $n_S(0)$is ground state superconducting electronsdensity.

From equation (4.2) ground state superconducting electronsdensitycan be expressed as

$$n_S(0) = \frac{4\eta_{ph} m^*}{2AK_B{}^2\varsigma_{GL}(0)} \quad ......(1.3)$$

In considering superconductor - normal metal – superconductor system (S-N- S) at a temperature much less than the transition temperature with two superconductors' layers being identical and conventional, their order parameter is given by theform(Andrei,2004).

$$\psi(r) = \left(\frac{n_s(0)}{2}\right)^{\frac{1}{2}} e^{i\theta} \quad .... \quad (1.4)$$

Order parameter is important in that if it is known explicitly, then almost complete information about the superconductor condensate can be obtained.

To obtain a relationship between order parameter with Ginzberg Landau Coherence length, equation (1.3) was substituted into equation (4.4) and the wave function was obtained as

$$\psi(r) = \left(\frac{4\eta_{ph} m^*}{2AK_B{}^2\varsigma_{GL}(0)}\right)^{\frac{1}{2}} = \left(\frac{2\eta_{ph} m^*}{AK_B{}^2\varsigma_{GL}(0)}\right)^{\frac{1}{2}} e^{i\theta} \quad .... (1.5)$$

The extrapolation length, b (final point to which the wave dies completely) for S–N interface is calculated, and it is given in terms of ς_0 and a as in equation (1.6), (Peters *et. al*, 2014).

$$b \approx \frac{\varsigma(0)^2_{GL}}{a} \qquad \text{........... (1.6)}$$

Where ς_0 is the intrinsic coherence length (coherent length at temperature T0) in S while a is inter-atomic distance in the normal metal. Using equation (4.6) in equation (1.5) gives equation (1.7).

$$\psi(r) = \left(\frac{2\eta}{AK_B}\frac{m^*}{(ab)^2}\right)^{\frac{1}{2}} \qquad \text{............... (1.7)}$$

Equation (1.7) shows an inverse variation of interparameter and inter-atomic distance, $a.h$

Given that $= \lambda k$ (Ziqiao, 2016).........(1.8)

where k is wave vector, λ is wavelength, V is linear velocity, h is plank constant. Equation (1.7) becomes;

$$\psi(x) = \left(\frac{2\eta_{ph} m \lambda^2 k^2}{AK_B h^2 (ab)^{\frac{1}{2}}}\right)^{\frac{1}{2}} e^{i\theta} \qquad \text{........... (1.9)}$$

but $\theta = kx$

In order to analyze the wave progression in the normal metal from S-N boundary, the order parameter is substituted into Fourier expression.

Fourier series states that; (Dass, 2008)

$$f(x) = \frac{a_0}{2} + a_1 Cosx + a_2 Cos2x + a_3 Cos3x + \ldots + a_n Cosnx + \ldots + b_1 Sinx + b_2 Sin2x + b_3 Sin3x + \ldots b_n Sinnx \qquad \text{.......... (1.10)}$$

Where $a_0, a_1, a_2 \ldots a_n, \ldots b_1, b_2, \ldots b_n$ are Fourier Coefficients of Fourier Constants and $f(x) = \psi(x)$ is the wave function.

$$a_0 = \frac{1}{\pi}\int_0^{2\pi} \psi(x)dx \qquad \text{........... (1.11)}$$

$$a_0 = \frac{1}{\pi}\int_0 \left(\frac{2\eta \ldots \lambda^2 k^2}{AK_B h^2 (ab)^{\frac{1}{2}}}\right)^{\frac{1}{2}} e^{i\theta} dx \qquad \text{........... (1.12)}$$

By applying Fourier Series Integral formula (Dass, 2008).

$$\int uv\,dx = uv_1 - u' v_2 + u'' v_3 - u''' v_4 + \ldots \qquad \text{............. (1.13)}$$

where

$$u' = \frac{du}{dx},\ u'' = \frac{d^2u}{dx^2}, \ldots,\ v_1 = \int v\,dx,\ v_2 = \int v_1\,dx$$

$$a_0 = \frac{1}{\pi}\left[\varrho\left(\frac{e^{ikx}}{ik}\right)\right]_0^{2\pi} \qquad \text{................. (1.14)}$$

where ϱ is $\dfrac{2\eta_{ph} m \lambda k}{AK_B h (ab)^{\frac{1}{2}}}$

By applying Fourier Series Integral formula expressed in equation (1.13), equation (1.21) is obtained.

$$b_n = \frac{\varrho}{\pi n}\left[e^{ikx}\left(-Sin(nx)\right) - \left(ike^{ikx}\right)\left(\frac{-Cos(nx)}{n}\right) + \left(i^2k^2e^{ikx}\right)\left(\frac{Sin(nx)}{n^2}\right) - \left(i^3k^3e^{ikx}\right)\left(\frac{Cos(nx)}{n^3}\right) + \ldots\right]_0^{2\pi} \qquad (1.21)$$

Simplifying equation 1.21, eqn. (1.22) is obtained.

$$Q\left[e^{2\pi ik}\left(Cos(2\pi)\right) + \ldots \frac{e^{2\pi ik}}{n} \ldots \frac{e^{2\pi ik}}{n} \ldots \left(Cos(0)\right) + ik \ldots - k\, n^2 Cos(0) - ik\, n^3 Sin(0) \right]$$

.... (1.27)

Using Euler Formula in equ. (1.27) resulted in equation (1.28)

$$b_n = \frac{Q}{\pi i}\left[1\left(\frac{k^2}{n^2}\right) - 1\left(\frac{k^2}{n^2}\right)\right] = 0 \qquad ......(1.28)$$

Equation (1.28) gives the Fourier constant b_n . The Fourier constant is zero because Fourier expansion for an even periodic function contains only cosine terms while for the odd periodic functions, there are only sine terms (Dass, 2008).

The Fourier Coefficients a_0, a_n and b_n were substituted into Fourier series expansion equation (1.10) and simplified to get wave function equation (1.32).

The Fourier equation is given as

$f(x) = \frac{a_0}{2} + a_n Cosnx + b_n Sinnx$, but $f(x) = \psi(x)$ (where $\psi(x)$ is order parameter), equation (1.29) can be obtained.

$$\psi(x) = 0 - \frac{Q\pi^2}{4a^2 n^3} Cos(nx) + 0 \quad ....(1.29)$$

$$\psi(x) = -\frac{Q\pi^2}{4a^2 n} Cos(nx) \quad ...... \quad (1.30)$$

$$\psi(x) = -\frac{Q\pi^2}{4a^2}\left(Cos(x) + \frac{1}{2} Cos(2x) + \frac{1}{3} Cos(3x) \right)$$

for $n=1,2,3,....$ .... (1.31)

$$\psi(x) = -\frac{\pi^2 Q}{4a^2} Cos(x) - \frac{\pi^2 Q}{32a^2} cos(2x) - \frac{\pi^2 Q}{108a^2} Cos(3x)$$

...... (1.32)

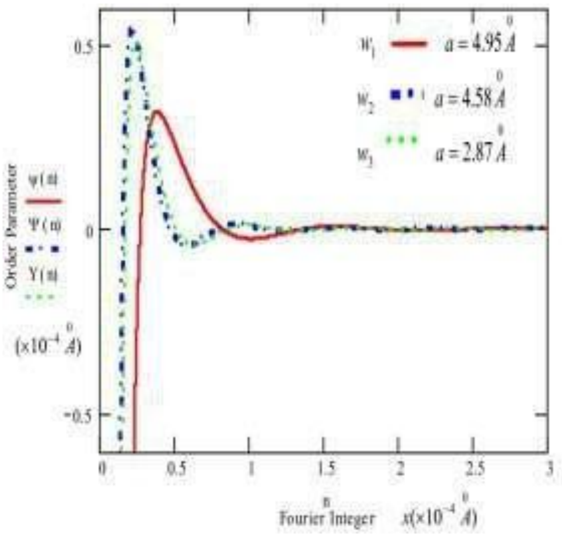
Equation (1.32) is the wave function of induced superconducting state

4.RESULTS AND ANALYSIS

4.1.Wave Function of Induced Superconductivity in Pure Metals.

From equation (1.30) Q for which metal was calculated as Q=0.0667 . The order parameter obtained in this research was a cosine function that produced a wave with maximum amplitude which decreases as the electron pairs penetrate deeper into the normal metal. The Order parameter was plotted against Fourier integer variable n for varying inter-atomic distances of lead Pb , Europium Eu and Iron Fe metals with 0 inter-atomic distances of 4.95 A, 4.58 A5and 2.87 Arespectively as shown infigure 5.1.

Figure 2: Variation of order parameter with inter-atomic distance of Pb , Eu and Fe



From figure 2, wavew_1 shows superconducting wave propagating into a lead metal. This wave had its highest amplitude at 0.54A^0 which was dropping as the wave penetrates into the metal and finally died off at $n=1.2\times10^{-4}$ ^0A . Its wavelength was$6.5\times10^{-5}A$. Wavew_2 shows a plot of order parameter against Fourier integer for europium metal with$a$=4.58A^0. It resulted into a wave with its highest amplitude of 0.50 ^0Aexhibiting a drop as the wave penetrates into the metal and later died at n=$1.3\times10^{-4}A^0$with a wavelength of $6.7\times10^{-5}A^0$. Iron metal with a=2.87^0A was represented by w_3 which is a wave that begun with an amplitude of 1.06 $A$and was reducing as the wave penetrateinto the metal. The wave then died off at n =1.5×10^{-4} A^0.

Lead metal exhibited the shortest wavelength followed by europium metal. Iron metal had the highest wavelength. This therefore showed that metal with largest inter-atomic spaces exhibits highest wave frequencies compared to that of metals with smaller inter-atomic spaces.

Extrapolation length of lead metal $b_{Pb}$was identified to be the shortest among the three metals while that of iron metal b_{Fe} was the longest. For a material to make a good superconductor through proximity effect, it should exhibit a longer extrapolation length that shows the final point to which the wave dies completely; superconductivity disappears beyond this point in the metal. This means that normal metals with shorter inter-atomic distances can exhibit better induced superconductivity through proximity effects.

In superconducting state electron pairing and long range phase coherence length both occurring at different temperatures are required. At the S-N junction the order parameter does not suddenly change from its maximum to minimum value. This is because there is no locality of the electrons inthe pure metals; therefore, properties of those electrons cannot change quickly. Electrons in thesuperconductor are ordered in pairs while in a pure metal, the electron order is gapless where single electron states are filled up to Fermi surface. On bringing both superconductor and pure metal together, the order of electrons in the system cannot change abruptly at the junction (Cherkez *et. al*, 2014)

The two systems (S-system and N-system) are in different temperatures. The pure metal has higher thermal temperature than that of the neighboring superconductor. This raises random motion of crystal lattice ions as cooper pairs pass through them. This is due to rise of thermal vibration of lattice ions as cooper pairs penetrate deeper into the metal. Since electron pairing is only possible when such vibrations are very low, the cooper pairs break when the vibrations becomes higher. This makes superconductivity to disappear as the cooper pairs move further into the N-system.

The paired state in the superconducting layer is carried over to the normal metal at the S-N boundary, where the pairing is destroyed by scattering events, causing the Cooper pairs to lose their coherence (Clerk, 1968). In normal metal there are empty states just above the Fermi energy. Electrons which occupy states at or energy near Fermi energy can easily jump into these empty states. When this happens they scatter off. This results into inelastic scattering leading to electric resistance (Saxena, 2012). Purity of the normal metal prolongs the penetration length of the cooper pairs into the normal metal. Penetration length of Cooper pairs into the normal metal is directly proportional to purity of the metal. In a superconductor, a gap in the electron density of state opens up around Fermi surface (Erker *et. al*, 2017).

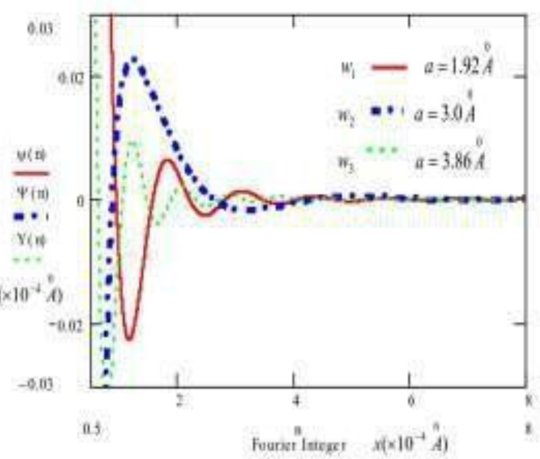
Once the superconductivity has been inducted into the normal metal, correlation decay into the normal metal is experienced from the interface due to scattering by the impurities. The phase angle of the order parameter is broken down by inelastic and spins flipping scattering process as the cooper pairs penetrates deeper into the normal metal (Annics *et. al* , 2008). Although electron pairing is a quantum effect, it can also be viewed and simplified classically. An electron in a normal metal behaves as a free particle (Eyyuphan *et. al,* 2016). Electrons repel each other due to their similar negative charges. In a superconductor as an electron move through the lattice it attracts positive ions that make up the rigid lattice of the metal. Distortion of the ion lattice emerges due to this attraction between them and moving electron. A positive charge density of the lattice in the vicinity is then increased which can attract another electron (Fritsch*et. al,* 2014). At long distances this attraction between two electrons can overcome electron repulsion, instead they pair up.

According Faraday's Law, the e.m.f. induced in a circuit is proportional to the time rate of change of the magnetic flux linkage in a normal conductor (Saxena, 2012). Therefore, when current flows through a normal conductor, it creates an associated alternating magnetic field around it. By magnetic field emerging into the metal, the superconductivity disappears. The effect of a small amount of nonmagnetic impurities also leads to electron pair breakings; it reduces superconductingtransition temperatures and facilitates the appearance of more single particle density of states at the Fermi energy (Cherkez *et. al*, 2014).

4.2.Wave Function of Induced Superconductivity in Superconducting Materials.

Variations of mercury cuprate *Hg*1223, Thalium curate *TI*1220, and iron based superconducting material $LnFeASO_{0.6}$ with Fourier integer are shown in figure 5.6.

Figure 3: Variation of Order parameter with Fourier integer *n* at higher *a* for Cuprates; *Hg*1223,*TI*1220and Iron based super conducting material; $LnFeASO_{0.6}$



Wave w_1 in this figure shows a plot of order parameter of $Hg1223$ (having a=1.92A). The wave had its highest amplitude of 0.21×10^{-4} ⁰A and a wavelength $2.13\times10^{-4} A$ at the S-S boundary; the amplitude recorded a continuous drop as n increase and as the wave progressed into the superconducting material, the wave then died off at n =2.64×10^{-4} A.

Wave $w2$ is a wave representing a variation between the order parameter and Fourier integer for the Thalium cuprate $TI1220$ with a=3.0 . The wave had an amplitude of $0.35m$ and a wavelength of 1.38×10^{-4} A. The iron based super conducting material; $LnFeASO_{0.6}$ with a =3.86 A produced wave w_3 with the highest amplitude of $0.42m$ and a wavelength of 1.12×10 A. Here the wave died at n =3.52×10^{-4} A

From the research results, it was noted that a superconductor with larger a records higher wave frequencies compared to those with shorter a. The penetration depth (extrapolation length b), of the wave was found to be longer in the superconducting materials with larger a, revealing that penetration depth of induced superconductor increase with increase in a . The frequency of the induced superconductor wave progression into the superconducting materials increases with increase in a . This result concur with Andrei, (2004) who found that the large spaces between the atoms can result to a larger displacement of lattice ions that may contribute to higher thermal ion vibrations.

In both pure metals and superconducting materials, penetration depth (extrapolation length b) is a vital parameter in the manufacture of a superconductor because it spells out the final point to which the wave dies completely; that is where induced superconductor ends in the neighboring material. Superconductivity at the boundary does not suddenly change from its highest value to a minimum value, it diminishes slowly as the pairs penetrate into either anther of metal or material and finally come to a minimum value. This means that in both cases, the wave begins with a amplitudes which later dies off as the electron pairs move further into the materials. In this finding the research noted that increase in inter-atomic distance and order parameter wave frequency in the superconducting material raises the extrapolation length. While increase in inter- atomic distance in pure metals lowers the extrapolation length.

This is because pure metals electrons are dressed by cloud of holes, the holes follow bare electrons when they move. Mobile electrons in solids also carry with them lattice polarization which is a cloud of phonon emerging as a result of electron phonon interaction. In pure metals holes dressing is more important than phonon dressing in current conduction while in superconductors phonon dressing dominates in the conduction mechanism. When phonon-electron coupling is very strong, the extent of lattice deformation due to moving electrons attains the order of lattice constant and the paired electron are trapped within the atomic lattice deformation by bipolarons. A rise in electron-phonon interaction shortens the coherent length. When it becomes shorter of the order of inter-atomic distance, the cooper pairs become farmionic making material to become normal metal (Shifa *et. al,* 2017). Shifa and the college further found out that as inter atomic-radius in the crystal varies polaron lifespan increase with increase in polaron radius. Small polarons are governed by short range interactions between electrons and phonons.

According to Finnemore *et. al*, (2013), as the wave penetrates through S-S border, the amplitude of the wave propagation is high but when moving in through the second superconductor the wave decays exponentially. This decay leads to low amplitude wave on a length scale of 10A combining a series of 10 atoms for copper based cuprates. According to Finemore the wave may not penetrate more than10A . The order parameter penetration depth into the S2 is inversely proportional to wave frequency (Frantino *et. al*, 2016). Hainze *et.al,* (2013) noted that the low frequency wavepenetrates the neighboring superconductor longer distance than that of higher frequency and some of the wave energy is being absorbed by the superconductor.

The proximity effect in S-S junctions is much higher than that of S-N junstions (Clerk, 1998). Experimental results agree with the finding of this research. This result also agrees with that of Greenblat *et.al*, (1990) who found out that order parameter dies off as a rises in the neighboring S2.

5.CONCLUSION

As discussed in this study, proximity effect refers to a change in penetration of cooper pairs into a normal material put in contact with a superconductor. The proximity effect at superconductor-superconductor and superconductor-pure metal interface were noted to produce damped oscillatory behavior of paired electron wave order parameter within the material. The wave function of induced superconductor was built and analysis of its behavior in the superconductor showed wave of cosine function. The waves had high amplitudes at both S-S and S-N boundaries which were dropping as the cooper pairs penetrate into the neighboring material. The amplitude and extrapolation length in the proximity effect at S-S junction were noted to be higher than that of S-N junction. Inter atomic space a and Fourier integer variable n were both found to have influence on extrapolation length b of the induced superconductor. In normal metals, materials with larger a recorded higher wave frequencies compared to those with smaller a . While in S-S the order parameter wave penetration depth of the wave was found to be longer in materials with larger a, revealing that penetration depth of induced superconductor increase with increase in a . The frequency of the wave was also identified to have an influence on extrapolation length. The frequency of the induced superconductor wave progression into both neighboring superconducting material and normal material increases with increase in a.

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