Pairing mechanism and transition temperature of Ba-Pb-BiO superconductors

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The nature of pairing mechanism in cubic perovskite BaPbBiO3 has been investigated by developing a model potential which involves electron-electron, electron-optical phonon as well as electron-plasmon interactions. The interaction potential was used to obtain the pairing parameters as coupling strength and Coulomb repulsive parameter. Coupled oscillations of electronic charge with longitudinal optical phonon describe the superconducting nature of bismuth oxides. Estimated value of coupling strength ($\lambda=0.84$) is consistent with a moderate attractive interaction. The screened Coulomb repulsive parameter ($\mu^*=0.22$) infers the poor screening of charge carriers with low carrier concentration and reflects a small density of states. The superconducting transition temperature ($T_c$) of BaPb$_{0.75}$Bi$_{0.25}$O$_3$ is evaluated as 15.5 K which is consistent with the earlier reported data. The analysis has led to the conclusion that a weak to moderate coupling exists and the coupling of charge oscillations with longitudinal optical phonon mode could be a reason to the superconductivity in Ba-Pb-BiO superconductors.

The occurrence of superconductivity in cubic perovskite oxide BaPb$_{1-x}$Bi$_x$O$_3$ ($x=0.25$, $T_c \approx 13$ K) provides an opportunity to understand the mechanism of pairing as well as the nature of superconducting state. The interest in BiO system is renewed with the recent findings of Ba$_{1-x}$K$_x$BiO$_3$ with superconducting transition temperature, $T_c=30$ K which have similar $T_c$ as those of La based cuprates. The copper oxide based superconductors are highly anisotropic in their physical properties due to the two dimensional (2D) character of the conducting copper oxide (CuO$_2$) planes. On the other hand, the non-transition metal compound BaPb$_{1-x}$Bi$_x$O$_3$ (BPBO) is isotropic as the oxygen octahedra form a three-dimensional (3D) network. The parent compound La$_2$CuO$_4$ is an antiferromagnetic insulator, instead BaBiO$_3$ is semiconducting with low density of states at the Fermi level. The high value of $T_c$ besides essential differences in copper and bismuth families have raised serious queries regarding the common pairing mechanism.

The parent compound BaBiO$_3$ is semiconducting, the breathing mode is completely softened and the static displacements of the oxygen atoms have been observed from the crystallographic studies. The chemical substitution of Pb in place of Bi introduces free charge carriers and the BiO lattice is modified. The resistivity and Hall-coefficient measurements revealed that the system BaPb$_{1-x}$Bi$_x$O$_3$ shows a metallic behaviour in the compositional range $0.0 \leq x \leq 0.05$. The superconducting nature is observed for $0.05 \leq x \leq 0.35$ with a maximum $T_c \sim 13$ K at $x=0.25$, despite of the fact that the charge carrier density ($n \sim 10^{21}$ cm$^{-3}$) and the density of states at the Fermi level ($n_{\text{bulk}}=0.1$ states/(eV unit cell spin)) are much smaller than the conventional superconductors with similar $T_c$'s. The metal to semiconductor transition in BPBO occurs at $x=0.35$ and exhibit semiconducting characteristics in the range $0.35 \leq x \leq 1.0$.

Band structure calculations on BaPb$_{1-x}$Bi$_x$O$_3$ have been performed by Mattheiss and Hamann. The Raman study of lattice vibrations together with infrared spectroscopy results confirms the presence of LO and TO breathing vibration in Ba-Pb-BiO perovskites. The electron-lattice interaction of Ba-Pb-BiO is studied microscopically by using the realistic electronic bands of BaBiO$_3$ reproduced by the tight binding model. The superconductivity was discussed in the frame work of strong coupling theory of electron-lattice interactions caused by the.
longitudinal modes of oxygen stretching/breathing vibration.

The reflectivity measurements have been carried out by Tajima et al.\textsuperscript{10} over a wide energy range and also over the whole compositional range in BaPb\textsubscript{1-x}Bi\textsubscript{x}O\textsubscript{3} superconductors. The phonon structure is observed by far-infrared optical and Raman scattering measurements and the plasma excitations in the visible and near infrared region. The existence of plasmons are well confirmed by Tajima et al.\textsuperscript{11} from the Electron-Energy Loss Spectroscopy (EELS) at the bismuth dopant level (x=0.27). This suggest the participation of collective excitation besides optical phonons in the pairing mechanism in BaPb\textsubscript{1-x}Bi\textsubscript{x}O\textsubscript{3} superconductors. However, the presence of oxygen isotope effect\textsuperscript{12} (coefficient $\alpha=0.22$) and the energy gap ratio ($\beta=2\Delta/K_B T_c=3.5\pm0.5$), now clearly indicate that usual electron-phonon interaction plays an important role. Batlogg et al.\textsuperscript{12} have suggested that anomalous high $T_c$ in BiO superconductors is not due to conventional strong electron-phonon coupling but the pairing is mediated by electronic excitations which involve the atomic displacements as a result of charge redistribution\textsuperscript{13}. During the recent past plasmon mechanism\textsuperscript{14} emerges as a central theme in the formation of additional pairing mechanism and could lead to high $T_c$ values in copper oxides. Recently, Varshney and Singh\textsuperscript{15} have made an attempt to study the joint phonon and plasmon mechanism in the lanthanum copper oxides based on Free electron layered electron gas model. The approach facilitates the various interactions, dielectric response function and the 2D acoustic phonon, plasmon modes by properly considering the layered structure. The purpose of the present paper is to study the role of charge oscillations as well as of the breathing phonon mode in the cubic perovskite Ba-Pb-BiO and to see what set of parameters can explain well the experimental measurements about the normal metallic state. Such studies on Ba-BiO systems have wide potential as the $T_c$ is high and resembles with CuO based superconductors. Earlier, Tachik and Takahashi\textsuperscript{16} have explained the superconductivity in copper oxides, when the pairing interaction is mediated by the charge transfer oscillations associated with LO phonons and suggested the similar mechanism in Ba-Pb-BiO\textsubscript{3} superconductors. In view of the earlier experimental and theoretical findings a model potential is developed including Coulombic, electron-optical phonon and electron-plasmon interactions to look for the pairing mechanism as well as physical parameters in the superconducting state. The approach is used to work out (a) the coupling strength ($\lambda$), (b) the screened Coulomb repulsive parameter ($\mu^*$), (c) the 2D acoustic plasmon energy ($\hbar \omega_p$), and (d) the coupled oscillations of electronic charge associated with longitudinal optical phonon energy ($\hbar \omega_L$) in Bismuth oxides. Finally, transition temperature for maximum $T_c$ doping concentration ($x$) is evaluated.

**Essential Formalism**

The parent BaPbO\textsubscript{3} compound is regarded as semimetal. The empty Pb(6s) band slightly overlaps with O(2p) band. Chemical substitution of Bi\textsuperscript{3+} in place of Pb\textsuperscript{4+} introduces one electron per one Bi atom in the empty Pb(6s) band which are the active charge carriers (electrons) of effective mass $m^*$ and will participate in the pairing mechanism. Besides these active charge carriers the contraction and expansion of oxygen octahedra around the Bi or Pb atoms will give rise to breathing modes of phonons. The Bi atom has two stable ionic states in the form of Bi\textsuperscript{3+} and Bi\textsuperscript{5+} which allows the valence of Bi atom to fluctuate even in the Pb\textsuperscript{4+} matrices. The dielectric constant of the oxide is given by a sum of ionic and electronic dielectric constants. The model dielectric constant is represented by

$$\varepsilon(q,\omega)=\varepsilon_{core}+\varepsilon_{pd}(q,\omega)+\varepsilon_{el}(q,\omega) \quad \ldots (1)$$

where, the first term is the polarizability of ionic core-electrons. In the frequency region of interest, $\varepsilon_{core}$ is assumed to be independent of frequency and is a constant ($=\varepsilon_\infty$). The electronic and ionic polarizabilities are represented by the second and third terms respectively. When an ionic semimetal is doped with the small number of electrons or holes, the crystal becomes metallic and the current carriers also contribute to the dielectric constant. A realistic calculation of $\varepsilon_{el}(q,\omega)$ requires a many body treatment for the behaviour of charge carriers and is rigorous. The random phase approximation forms of polarizability are widely used to describe the plasma behaviour to see the coupling effects...
and recently, Mahan and Wu have applied it to the copper oxides. In the long wave length limit \((q\to 0)\), the electronic polarizability is expressed as
\[
P_e(q,\omega) = D_1/(\Delta_1^2 - \omega^2)
\]  
(2)
where \(D_1 = \Omega_p^2\)
(3)
and \(\Delta_1^2 = q^2 V_F^2/2\)
(4)
with \(V_F\) represents the Fermi velocity.

The ionic polarizability is
\[
P_i(q,\omega) = \varepsilon_{\infty}, \frac{\omega_{\text{LO}}^2 - \omega_{\text{TO}}^2}{\omega_{\text{TO}}^2 - \omega^2}
\]  
(5)
where \(\omega_{\text{LO}}\) and \(\omega_{\text{TO}}\) are the frequencies of LO and TO breathing vibrations. For the sake of simplicity, single optical phonon whose vibrational frequencies are independent of wave vector \((q)\) has been considered.

The model dielectric function for the polarized waves with the above description becomes
\[
\varepsilon(q,\omega) = \varepsilon_{\infty} + \frac{D_1}{\Delta_1^2 - \omega^2} + \frac{\varepsilon_{\infty} D_2}{\Delta_2^2 - \omega^2}
\]  
(6)
\[
\varepsilon(q,\omega) = \varepsilon_{\infty} \left[ 1 + \frac{A_1}{\Delta_1^2 - \omega^2} + \frac{D_2}{\Delta_2^2 - \omega^2} \right]
\]  
(7)
where, \(A_1\) denotes a screened plasma frequency, \(D_2 = \omega_{\text{LO}}^2 - \omega_{\text{TO}}^2\) and \(\Delta_2^2\) as \(\omega_{\text{TO}}^2\), respectively. The spectral intensity of the polarized wave is expressed as
\[
\eta(q,\omega) = -\frac{1}{\pi} \text{Imag} \left[ \frac{\varepsilon_{\infty}}{\varepsilon(q,\omega)} \right]
\]  
(8)
where, the dielectric constant is given by Eq.(6). Physically it corresponds to the excitation density of the polarized waves.

The main input parameter about the concerned material which determines the critical transition temperature, is the dynamic interaction potential \(V(q,\omega)\) or equivalently \(\varepsilon^{-1}(q,\omega)\) of the system. If to the first approximation, \(\varepsilon^{-1}(q,\omega)\) is identified with the inverse longitudinal dielectric function of the system, it can be associated with different longitudinal modes, corresponding to the exchange of phonons, plasmons, having poles at the respective modes. Since the interest is in separation of the individual contributions of \(\varepsilon^{-1}(q,\omega)\) from different longitudinal modes, the inversions of Eq. (6) is done in the form
\[
\varepsilon^{-1}(q,\omega) = \varepsilon_{\infty} \left[ 1 + \sum_{i=1}^{2} \frac{f_i}{\omega^2 - \Omega_i^2} \right]
\]  
(9)
where \(\Omega_i\) are the frequencies of two longitudinal modes and the resonant frequencies are given by
\[
(\Omega_1^2 - \Delta_1^2)(\Omega_2^2 - \Delta_2^2) + A_1(\Delta_2^2 - \Omega_2^2) = 0
\]  
(10)
The effective interaction potential \(V(q,\omega)\) is the sum of electronic and ionic contributions, \(V(q,\omega) = V_e(q)\ v_e^{-1}(q,\omega)\) from the individual longitudinal modes. The oscillator strength is defined as
\[
f_i = \frac{2}{\pi} \left[ \frac{\Omega_1 - \Delta_i^2}{\Omega_i^2 - \Omega_j^2} \right]
\]  
(11)
It is suffice to see that following sum rules are valid,
\[
\sum_{i=1}^{2} \Omega_i^2(q) = D_1 + D_2 + \Delta_1^2 + \Delta_2^2
\]  
(12)
\[
\sum_{i=1}^{2} f_i(q) = D_1 + D_2
\]  
(13)
\[
\sum_{i=1}^{2} f_i(0) / \Omega_i^2(0) = 1
\]  
(14)
Here, \(f_i(0) / \Omega_i^2(0)\) is the limiting value of \(f(q) / \Omega_i^2(q)\) in the long wavelength limit.

This states that
\[
\varepsilon(q\to 0, 0) \to 0 \text{ when } \omega = 0
\]
Zero's of the model dielectric function will yield two modes of the polarized waves and the frequencies of the coupled mode in the long wavelength limit are
\[
2\Omega_\pm^2 = \left[ \Omega_p^2 + \Delta_1^2 + \omega_{\text{LO}}^2 \right]
\]  
(15)
\[
\pm \left[ (\Omega_p^2 + \Delta_1^2 + \omega_{\text{LO}}^2)^2 - 4(\omega_{\text{LO}}^2 \Delta_1^2 + \omega_{\text{TO}}^2 \Omega_p^2) \right]^{1/2}
\]  
(16)
Further simplification yields
\[
\Omega_i^2 = \Omega_p^2 + \Delta_1^2
\]  
(17)
shows the 2D acoustic plasmon characteristics. The lower mode is expressed as
\[
\Omega_\pm^2 = \frac{\omega_{\text{LO}}^2 + \omega_{\text{TO}}^2}{2 + (\omega_{\text{LO}}^2 / \Omega_p^2)}
\]  
(18)
which is basically coupled charge oscillation with optical phonon mode.
The effective longitudinal dielectric function in terms of 2D acoustic plasmon mode \((\hbar \Omega_a)\) and coupled charge oscillation with phonon-mode \((\hbar \Omega_p)\) is now written as
\[
\varepsilon_{\text{eff}}(q, \omega) = \frac{(\omega^2 - \Omega_a^2)(\omega^2 - \Omega_p^2)}{(\omega^2)(\omega^2 - \Delta_p^2)}
\]
and the interaction potential takes the form
\[
V(q, \omega) = V(q) \varepsilon_{\text{eff}}^{-1}(q, \omega)
\]
\[
= \frac{2\pi e^2}{q \varepsilon_0} \left[ 1 + \frac{\Omega_a^2(\Omega_a^2 - \Delta_p^2)}{(\omega^2 - \Omega_a^2)(\Omega_a^2 - \Omega_p^2)} + \frac{\Omega_p^2(\Omega_p^2 - \Delta_p^2)}{(\omega^2 - \Omega_p^2)(\Omega_a^2 - \Omega_p^2)} \right] \]
\[
\text{Physically, the interaction potential } V(q, \omega) \text{ gives the coupling strength for scattering a Fermion from the } K \text{ to } K' \text{ state and it works to break Cooper pairs in the system and to stabilize the superconducting state. From Eq. (16) } V_{KK'} \text{ takes three values, } V_c, V_{ph} \text{ and } V_{pl}, \text{ depending upon the regions of electron energy as}
\]
\[
V_{KK'} = -V_{ph} \quad \text{for } \omega < \Omega_a
\]
\[
V_c \quad \text{for } \Omega_a - |q| < E_F
\]
\[
V_{pl} \quad \text{for } E_F < |q| < \Omega_p
\]
Here, \(E_F\) denotes the Fermi energy. The terms \(V_c, V_{ph} \text{ and } V_{pl}\) express the Coulomb, electron-coupled phonon-plasmon and electron-plasmon interactions, respectively.

In the strong-coupling theory, the superconducting transition temperature \(T_c\) requires the information of the screened Coulomb’s repulsive parameter \((\mu^*)\) and the coupling strength \(\lambda\) between neighbouring electrons through phonons. The averaged Coulomb repulsive parameter is
\[
\mu = \frac{N(O)}{2K_F^2} \int_{q_F}^{K_F} \text{Real } V(q, \omega) q d q
\]
to get
\[
\mu = \frac{1}{a_B K_F} \left[ 1 - \frac{\ln(1 + a_B K_F)}{a_B K_F} \right]
\]
where \(a_B = (e^2 \hbar^2/m^*e^2)\) is the Bohr radius and \(N(O) = (m^*/2\pi \hbar^2)\) denotes the electronic density of states at the Fermi level. Finally, the screened Coulomb repulsive parameter \((\mu^*)\) represents the Coulomb electron-electron interaction as
\[
\mu^* = \frac{\mu}{1 + \mu \ln(E_F/\hbar \Omega_a)}
\]
The coupling parameter \(\lambda\) is related to the Eliashberg function \(\alpha^2(\omega) F(\omega)\) through
\[
\alpha^2(\omega) F(\omega) = \frac{\int_0^1 \text{Imag } V(q, \omega) q d q}{\omega}
\]
and the Eliashberg function is defined as
\[
\alpha^2(\omega) F(\omega) = \frac{N(O)}{2K_F^2} \int_{q_F}^{K_F} \text{Imag } V(q, \omega) q d q
\]
\[
to give \lambda as
\]
\[
\lambda = \frac{2m^*e^2}{\hbar^2 K_F^2} \frac{\Omega_p^2}{(\omega_{LO}^2 - \omega_{TO}^2)}
\]
Using the screened Coulomb parameter and the coupling strength, at the maximum value of coupled charge oscillations with longitudinal optical phonon frequency, \(T_c\) has been calculated for BaPbBiO superconductor using\(^{18}\)
\[
T_c = 0.7 \Omega_a \exp \left[ \frac{1 + \lambda}{\lambda - \mu^*} \right]
\]
Using the developed expressions, the superconducting transition temperature \((T_c)\) in BaPb\(_{1-x}\) Bi\(_x\)O\(_3\) \((x=0.25)\) has been computed.

Results and Discussion

In order to compute the superconducting state parameters at maximum doping concentration, i.e., \(x=0.25\) in BaPb\(_{1-x}\)Bi\(_x\)O\(_3\) compound, the realistic physical parameters based on the experimental data have been used. The effective mass of the charge carrier (electron) is evaluated as
\[
\frac{m^*}{m_e} = \frac{N(E_F)}{N(E_F^*)}
\]
with \(N(E_F)\) as the band density of states calculated from the electronic specific heat coefficient \((\gamma)\) data\(^9\) as 1.5 mJ mol\(^{-1}\)K\(^2\). The value of \(N(E_F)\) is \(1.38 \times 10^{39}\) states/mJ/mol has been used as reported earlier by Itoh et al.\(^5\) to obtain \(m^* = 1.5 m_e\). The background dielectric constant \(\varepsilon_0\) is taken as 4.0 (ref. 10). The Fermi velocity is deduced as 2.26 \times 10^7 cm s\(^{-1}\).

The Coulomb interaction among the adjacent ions in an ionic crystal is expressed in terms of the potential\(^{20}\).
\[ \Phi(r) = -(Ze)^2 \left[ \frac{1}{r} - \frac{a}{r^n} \right] \]  

where \( a \) is the repulsion force parameter between the ion cores. The effective ion charge is denoted as \( Ze \) and is taken as \(-1.7e\). The elastic force constant \( k \) can be derived from the \( \Phi(r) \) at the equilibrium interionic distance \( r_0 \) as

\[ k = \frac{\partial^2 \Phi}{\partial r^2} \bigg|_{r_0} = (Ze)^2 \left[ \frac{n-1}{r_0^n} \right] \]  

where \( n \) is the index number of the repulsive potential and \( r_0 \) is taken as 2.21 Å. The longitudinal and transverse optical breathing vibrations are expressed as

\[ \omega_{LO}^2 = \frac{1}{\mu(m)} [k + \beta^*] \]  

and \[ \omega_{TO}^2 = \frac{1}{\mu(m)} [k - \beta^*] \]  

where \( \mu(m) \) is the reduced mass, \( \mu(m) = \frac{M(\text{Pb})M(\text{O})}{M(\text{Pb}) + M(\text{O})} \) and is 14.84 amu. The force parameter \( \beta^* \) is

\[ \beta^* = \frac{8\pi (Ze)^2}{3\Omega} \]  

with \( \Omega \) is the volume of unit cell and is taken to be 316.3 Å³ (ref. 7). The charge carrier density is \( 3.2 \times 10^{21} \text{ cm}^{-3} \) (ref. 21). The force parameters have been deduced as \( k = 6.169 \times 10^{14} \text{ g s}^{-2} \) and \( \beta^* \) as \( 1.763 \times 10^{14} \text{ g s}^{-2} \) respectively.

Using these realistic physical parameters based on experimental observations, \( \hbar \Omega, \) and \( \hbar \Omega' \) modes have accepted. The scattering of charge carriers at the Fermi surface is considered for all values of scattering angle\( \theta \). The wave vector \( q = (2K_F \sin\theta) \) can therefore take maximum values up to \( 2K_F \). It is evident from Eqs (13) and (14) that \( \hbar \Omega(q) \) is a characteristic 2D acoustic plasmon mode and \( \hbar \Omega' \) shows the coupled charge oscillations with optical phonon behaviour. The maximum 2D acoustic plasmon energy \( (\hbar \Omega) \) is obtained as 0.86 eV and coupled mode \( (\hbar \Omega') \) is deduced as 37.00 meV. The nature of interaction potential \( V_{kk'} \) is shown in Fig. 1. It is inferred that for the range \( \omega < \Omega, \Omega' < |\omega| < \Omega, \) the interaction potential shows the attractive characteristic while for \( |\omega| < \Omega < \Omega', \) it is repulsive.

The values of \( E_F \) and \( \mu \) have been obtained as 0.217 eV and 0.39 respectively. Estimated coupling strength in between the neighbouring electrons is 0.84 which favours the weak to moderate coupling theory. The screened Coulomb repulsive parameter is calculated as \( \mu^* = 0.22 \) for the maximum value of coupled frequency (37.00 meV) which shows the poor screening. With these parameters, \( T_c \) has been deduced as 15.50 K, which is higher by 16\% than the reported \( T_c \) of 13 K. This allows one to propose that the coupled charge oscillations with longitudinal optical phonons plays a key role and make a good explanation of the mechanism of superconductivity in Ba-Pb-BiO₃ compounds. Besides, evaluating \( T_c \) at maximum doping concentration, attempt has also been made to obtain at different values of doping concentration. The obtained results are, \( x = 0.15, \)
$T_c=10.35\,\text{K (9 K)}$, $x=0.20$, $T_c=12.76\,\text{K (11 K)}$ and $x=0.30$, $T_c=13.22\,\text{K (11.5 K)}$. The experimental data are given in brackets. These results on $T_c$ with $x$ in BaPbBiO superconductors are although higher but within the range of experimental reported data. Furthermore, efforts have been made to obtain a relationship between $\lambda$, $\mu^*$ and $T_c$ in the proposed approach. In this context taking $\lambda=0.847$ as constant and $\lambda$ on varying $\mu^*$, it was observed that for this value of $\lambda$, $T_c$ decreases with the increased value of $\mu^*$ depicting that for the higher values of $T_c$, the screening parameter should possess low values (Fig. 2). Besides this, the dependence of $T_c$ on $\lambda$ for a fixed value of $\mu^*(0.22)$ has been worked out and is plotted in Fig. 3. It is observed that $T_c$ increases with the increasing value of coupling parameter ($\lambda$). The dependence of $\mu^*$ on $\lambda$ for a fixed value of $T_c=15.5\,\text{K}$ is shown in Fig. 4. It is noticed that $\mu^*$ monotonically increases for the higher values of $\lambda$. From these observations, it may clearly be seen that $T_c$ depends on $\lambda$ as well as $\mu^*$. Thus it has been proposed that for high $T_c$ values, $\mu^*$, must be smaller and $\lambda$ values will be higher than 1.0. The low value of $T_c$ for $\lambda=0.84$, $\mu^*=0.22$ and $\Omega=37.00\,\text{meV}$ is in the weak to moderate coupling theory and the choice of parameters is reasonable for Ba-Pb-BiO superconductors.

Conclusions

In this paper, the cubic perovskite BaPb$_{1-x}$Bi$_x$O$_3$ ($T_c\cong13\,\text{K},\,x=0.25$) has been studied with emphasis on the coupled oscillations of electronic charge and breathing vibrations of oxygen. Doping of Ba$^{++}$ in place of Pb$^{++}$ introduces free electrons in the empty Pb (6$s$) band and a strong Coulomb interaction acts between electrons. These electrons couple with the breathing vibration of oxygen as well as charge oscillations in the system. The interaction generates oscillations of the electronic charge and the optical phonons. For simplicity, a single optical phonon mode has been considered whose vibrational frequencies are independent of wave number. The spectral intensity of the charge oscillations is extremely strong to the bare optical phonons. The superconducting transition temperature ($T_c$) has been investigated critically. The appropriateness of the present approach depends on the proper care of the charge oscillation and breathing vibrations. Due to its simplicity, the estimated value of $T_c$ is within the range of reported observations. Deduced values of $\lambda=0.84$ and $\mu^*=0.22$ for maximum $\hbar\Omega=37.00\,\text{meV}$ are quite reasonable and is a good set of physical parameters estimated from the experimental observations to yield high $T_c$ values as of 13 K despite of the low values of the charge carrier density as well as the density of the states at the Fermi level. The main conclusion is that the BaPb$_{1-x}$Bi$_x$O$_3$ is a weak to moderate coupled superconductor ($\lambda$ is nearly 1.0 or less) with strong interaction between electrons and high energy coupled charge oscillations and breathing modes of oxygen ($\hbar\Omega=37.00\,\text{meV}$). The physical parameters other than $T_c$ in conventional superconductors are extremely varied, but those of highest $T_c$ are characterized by a large density of states at the Fermi level, which leads to a comparatively large value of $\lambda$ and thus to high value of $T_c$. Thus the nature of superconducting state as well as pairing mechanism in BaPb$_{0.75}$Bi$_{0.25}$O$_3$ is well explained by
the coupled charge oscillations with longitudinal optical phonons.

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