PAIRING MECHANISM AND SUPERCONDUCTING STATE PARAMETERS OF CUBIC PEROVSKITE $\text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3$

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Abstract

We develop an effective three-dimensional dynamic interaction, which incorporates screening of charge carriers by optical phonons and plasmons, to discuss the nature of the pairing mechanism leading to superconductivity in cubic perovskite $\text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3$. The potassium-doped barium-bismuth oxide system ($\text{Ba-K-BiO}$) is treated as an ionic solid containing carriers and a model dielectric function is set up which fulfills the appropriate sum rules on the ionic and electronic polarizabilities. The values of the coupling strength and of the Coulomb interaction parameter indicate that the superconductor is in the strong coupling regime. Following strong-coupling theory, the superconducting transition temperature of optimally doped $\text{Ba-K-BiO}$ is estimated as $30$ K. The energy gap ratio is slightly enhanced and the isotope exponent is severely reduced relative to the BCS values. The present analysis points to the importance of both plasmons and optical phonons in determining the effective electron-electron interaction leading to superconductivity in doped cubic perovskites.
1. Introduction

Cubic \(\text{Ba}_{1-x}\text{K}_x\text{BiO}_3\) has the highest superconducting transition temperature \((T_c \sim 30\,\text{K})\) for \(x \sim 0.4\) among oxide superconductors not containing copper [1]. A most striking feature of this system is the absence of metal-oxygen planes, which are believed to be crucial in producing a high transition temperature in cuprates. The parent compound \(\text{BaBiO}_3\) is diamagnetic and has a body-centred monoclinic \((I2/m)\) structure. The K-doped compound \(\text{Ba}_{1-x}\text{K}_x\text{BiO}_3\) (Ba-K-BiO) exhibits superconductivity in the range \(0.37 \leq x \leq 0.5\). The Bi-O-Bi bonds in the K-doped system form an orthorhombic or a simple cubic perovskite structure depending on \(x\) [2]. Despite intense interest in three-dimensional Ba-K-BiO, the question of the electron pairing mechanism which is responsible for superconductivity at \(T_c \sim 30\,\text{K}\) and for the magnitude of the electron-electron coupling remains open. As the K-doped system is diamagnetic [3] and there is no evidence for static magnetic order [4], the magnetic pairing mechanisms as proposed for cuprates can be excluded for this material.

The Bardeen-Cooper-Schrieffer (BCS) theory for conventional superconductors [5] invokes electron-phonon coupling for Cooper-pair formation. Optical phonons are important in an ionic crystal such as Ba-K-BiO and Raman scattering of light as well as inelastic neutron scattering have been used to probe its phonon structure. The Raman spectrum of superconducting \(\text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3\), shows a strong peak near 348 cm\(^{-1}\) (43 meV), due to high-energy optical phonons coupled to electronic states [6]. Inelastic neutron scattering experiments [7] show that the phonon spectrum in \(\text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3\) comprises two bands near 30 and 60 meV, which are due to oxygen vibrations. Subsequently, Braden et al. [8] found that the highest longitudinal optical (LO) branch at \(-17 \,\text{THz}\) is associated with Bi-O bond stretching vibrations. These experimental studies indicate that in Ba-K-BiO the carriers may be coupled to high-energy oxygen vibrations.

Tunnelling spectroscopy can provide a direct measure of the interactions responsible for superconductivity, even though high-quality tunnel junctions on high-\(T_c\) materials are difficult to obtain. High-resolution tunnelling measurements on polycrystalline \(\text{Ba}_{1-x}\text{K}_x\text{BiO}_3\) \((x = 0.375,\,T_c \sim 29\,\text{K})\) have been reported by Zasadzinski et al. [9]. The tunnelling data reveal well-resolved phonon structures corresponding to
optical modes of the oxygens in the range 40–65 meV. Huang et al. [10] have demonstrated that high-energy optical phonons are involved in the carrier pairing, with a coupling constant $\lambda$ near unity and a zero-temperature energy gap ratio $(2\Delta(0)/k_BT_c)$ of $3.8 \pm 0.1$. Other tunnelling measurements on thin films [11] and single crystals [12] of Ba-K-BiO also favour the participation of oxygen optical phonons (in the range 20-70 meV) in the pairing mechanism, with an energy gap ratio in the range 3.5–3.8. Infrared spectroscopy yields an energy gap ratio of $3.5 \pm 0.5$ [13].

The phonon contribution to pairing can often be gauged from the shift in $T_c$ due to substitution of constituent elements by their isotopes. Batlogg et al. [14] measured the oxygen isotope effect in $\text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3$ and found a severely reduced isotope exponent ($\alpha_0 \sim 0.2 - 0.25$) relative to the BCS value for conventional superconductors ($\alpha_\text{BCS} = 0.5$). Kondoh et al. [3] find an exponent $\alpha_0 = 0.35 \pm 0.05$. Zhao et al. [15] also report a reduced value of $\alpha_0 = 0.2-0.3$ and find that $\alpha_0$ increases with decreasing K content. On the other hand, other groups have observed a large oxygen isotope effect. Hinks et al. [16] from their $dc$ resistivity and $ac$ susceptibility measurements find a shift of $\Delta T_c = 1.35 \pm 0.05$, leading to $\alpha_0 = 0.41 \pm 0.03$. Subsequently, Loong et al. [17] from their inelastic neutron scattering measurements together with molecular dynamics simulation report a value of $\alpha_0 = 0.42 \pm 0.05$. Studies of the oxygen isotope effect in Ba-K-BiO have thus led to conflicting results, with either phonon-mediated pairing [16,17] or non-phonon pairing [3,14,15] being proposed.

Among the non-conventional mechanisms which have been invoked for high-$T_c$ copper oxides, screening by collective charge fluctuations (plasmons) [18] is believed to be important in some materials. Measurements X-ray photoemission and reflectance have probed the electronic structure of Ba-K-BiO superconductors. The energy loss structure of core level spectra reveals a free-carrier plasmon at about 1 eV [19]. From the reflectance spectrum of $\text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3$ [20] the plasmon lies near 1.6 eV. This implies that carrier charge fluctuations are large in the K-doped oxides and may contribute to the pairing mechanism.

The strong coupling of the carriers to the oxygen vibrations as shown in the tunnelling spectra [9-12] together with the Raman, photoemission and reflectance studies [6,19,20] have provided the motivation for the present work. Here, we evaluate
a pairing mechanism in Ba-K-BiO as arising from the coupling of the carriers to both optical phonons and plasmon excitations. Specifically, we shall aim at assessing whether this mechanism can explain the large binding energy and a critical temperature of 30 K. We may also refer at this point to the work of Tachiki and Takahashi [21], who have attributed superconductivity in La- and Y-based cuprates to pairing mediated by charge transfer oscillations associated with LO phonons and suggested a possible relevance to K-doped Bi oxides, as well as to the work of Shirai et al. on Bi oxides [22], who find a strong frequency renormalization for the highest LO phonons due to doping.

The plan of the paper is as follows. In sect. 2 an effective interaction potential for Ba-K-BiO is developed by studying the collective excitations of ions and carriers. The random phase approximation (RPA) is adopted for the polarizabilities and leads to a model dielectric function obeying the appropriate sum rules. The zero’s of the dielectric function yield two modes, namely a low-energy plasmon and a mixed optical phonon-plasmon mode. The static limit of the dielectric function is then used to calculate the effective coupling strength and hence the transition temperature $T_c$. The isotope effect exponent and the energy gap ratio are also estimated. The details of the numerical analysis and its results are discussed in section 3. A summary and our main conclusions are presented in section 4.

2. The model
We start by giving a brief description of the cubic perovskite $\text{Ba}_{1-x}\text{K}_x\text{BiO}_3$. The compound $\text{BaBiO}_3$ is a diamagnetic insulator, with a gap opened at the centre of the Bi(6s) – O(2p) antibonding band by the formation of charge density waves. The formal charge state of the Bi ions is +4, and since the Bi atom has five valence electrons (two 6s and three 6p) an average of one valence electron is left on each Bi ion. The chemical substitution of monovalent alkali K at the divalent Ba sites introduces free charge carriers (holes). Further, the contraction and expansion of oxygen octahedra around the Bi ions will lead to breathing phonon modes.

We discuss next the dielectric function of such an ionic solid containing electronic carriers.
2.1. Dielectric function

The Fourier transform of the interaction potential between two carriers has the form

\[ V(q, \omega_{kk'}) = \frac{4\pi \varepsilon^2}{q^2 \varepsilon(q, \omega_{kk'})} \]  

with \( q = k - k' \) and \( \omega_{kk'} = (E(k) - E(k'))/\hbar \). \( V(q, \omega_{kk'}) \) essentially describes the coupling strength for the scattering of a fermion from the state \( |k> \) to the state \( |k'> \).

The dielectric function \( \varepsilon(q, \omega) \) of the metal oxide in Eq. (1) is a sum of ionic and carrier contributions and must be negative for an attractive interaction.

The ionic dielectric function in the insulating state is expressed as

\[ \varepsilon_{\text{ion}}(q, \omega) = \varepsilon_\infty + P_1(q, \omega) \]  

Here, \( \varepsilon_\infty \) is the high-frequency dielectric constant accounting for core-electron polarization and \( P_1(q, \omega) \) is the polarizability from the ionic displacements, that we take as [23]

\[ P_1(q, \omega) = \frac{\varepsilon_\infty (\omega_{\text{LO}}^2 - \omega_{\text{TO}}^2)}{\omega_{\text{TO}}^2 - \omega^2} , \]  

\( \omega_{\text{LO}} \) and \( \omega_{\text{TO}} \) being the frequencies of the longitudinal and transverse optical vibrations. For simplicity we are describing the phonon modes of the system by a single LO mode and the associated TO modes, and further neglect the dispersion of these modes.

On doping the compound becomes conducting and the free charge carriers contribute to the dielectric function through a polarizability function \( P(q, \omega) \). While a realistic calculation of \( P(q, \omega) \) requires a detailed knowledge of eigenstates and eigenvalues for the carriers, an RPA form of the carrier polarizability is widely used to describe the plasmon excitation in a simple manner [23]. In particular, for a single-band model of carriers with density \( n \) and effective mass \( m^* \), the RPA yields

\[ P(q, \omega) = \frac{\Omega_p^2}{(q^2 v_F^2/2) - \omega^2} . \]  

Here, \( \Omega_p = \sqrt{4\pi n e^2/ m^*} \) is the 3D plasma frequency and \( v_F \) is the Fermi velocity.
The model dielectric function of a conducting oxide such as Ba-K-BiO is thus written as
\[ \varepsilon(q,\omega) = \varepsilon_{\infty} + \frac{\varepsilon_0 D_1^2}{A_1^2 - \omega^2} + \frac{D_2^2}{A_2^2 - \omega^2}, \quad (5) \]

where \( D_1^2 = \omega_{LO}^2 - \omega_{TO}^2, A_1^2 = \omega_{TO}^2, D_2^2 = \Omega_p^2 \) and \( A_2^2 = q^2 v_f^2 / 2 \). Equation (5) leads to a two-coupled-oscillator form of the inverse dielectric function, whose resonances (at frequencies \( \Omega_i(q) \), say) are found by setting \( \varepsilon(q,\Omega) = 0 \). This condition yields
\[ (\Omega^2 - A_1^2)(\Omega^2 - A_2^2) + D_1^2(\Omega_2^2 - \Omega^2) + D_2^2(\Omega_1^2 - \Omega^2) = 0 \quad (6) \]

and hence the eigenmode frequencies of the coupled optical phonon-plasmon system are
\[ 2\Omega_{\pm}^2 = [\omega_{LO}^2 + \Omega_{ps}^2 + A_2^2] \pm [(\omega_{LO}^2 + \Omega_{ps}^2 + A_2^2)^2 - 4(\omega_{LO}^2 A_2^2 + \omega_{TO}^2 \Omega_{ps}^2)]^{1/2} \quad (7) \]

with \( \Omega_{ps} = \Omega_p / \varepsilon_{\infty} \). It is easily checked that these eigenfrequencies and the corresponding oscillators strengths \( f_i(q) \) obey the sum rules \( \Omega_1^2(q) + \Omega_2^2(q) = D_1^2 + D_2^2 + A_1^2 + A_2^2 \) and \( f_1(q) + f_2(q) = D_1^2 + D_2^2 \). A further sum rule is imposed at long wavelengths by the condition \( \varepsilon^{-1}(q \to 0, 0) \to 0 \) for static screening in a conductor.

Further simplification is achieved by treating the second term under the square root in Eq. (7) as small. This yields
\[ \Omega_i^2 = \Omega_{ps}^2 + A_2^2 \quad (8) \]

for the upper mode in the adiabatic approximation, which is the dispersion relation of a plasmon. The lower mode frequency is
\[ \Omega_-^2 = \frac{\omega_{LO}^2 A_2^2 + \omega_{TO}^2 \Omega_{ps}^2}{\omega_{LO}^2 + \Omega_{ps}^2 + A_2^2}, \quad (9) \]

again in the adiabatic approximation. This gives \( \Omega_- = \omega_{TO} \) at long wavelengths. However, due to the appreciable value of \( \varepsilon_{\infty} \) and to the low density of carriers in Ba-K-BiO, the LO frequency gives a better approximation to \( \Omega_- \) away from long wavelengths, where \( A_2^2 \) becomes larger than \( \Omega_{ps}^2 \).
Finally, the dielectric function can be rewritten in terms of the solutions in Eq. (7) for the coupled optical phonon-plasmon modes as

\[ \varepsilon(q,\omega) = \varepsilon_\infty \ \frac{\left(\omega^2 - \Omega_s^2\right) \left(\omega^2 - \Omega_p^2\right)}{\left(\omega^2 - \omega_{\text{TGO}}^2\right) \left(\omega^2 - \omega_{\Gamma}^2\right)} . \] (10)

The effective interaction potential is given by \( V(q,\omega) = 4\pi e^2/q^2\varepsilon(q,\omega) \). It consists of the sum of three terms, namely the direct Coulomb repulsion, a term from the exchange of free-carrier excitations and a term from the exchange of optical phonons.

As an application, the effective strength of the coupling between carriers in the superconducting state of Ba-K-BiO is evaluated in the following subsection.

2.2. Effective coupling strength

The evaluation of \( T_c \) requires information about the electron-electron and the electron-phonon coupling strengths. The effective Coulomb interaction between carriers is introduced by means of the pseudo-potential parameter \( \mu^* \) [24], that we evaluate within the 3D model that we have presented above.

We define the renormalized Coulomb repulsive parameter [24] as

\[ \mu^* = \mu / \left[ 1 + \mu \ln \{ \varepsilon_F / \hbar\omega_{\text{LO}} \} \right] , \] (11)

where (for reasons explained under Eq. (9)) we have set the cut-off frequency equal to the phonon frequency \( \omega_{\text{LO}} \). We write the Coulomb strength parameter \( \mu \) in Eq. (11) as \( \mu = N(\varepsilon_F)U \), where \( N(\varepsilon_F) \) is the density of states at the Fermi energy \( \varepsilon_F \) and \( U \) is the static screened interaction \( V(q,\omega = 0) \) averaged over the Fermi sphere. From Eq. (5) we have

\[ \varepsilon(q,\omega = 0) = \varepsilon_0 + \frac{4\pi ne^2}{\varepsilon_F q^2} . \] (12)

Here, \( \varepsilon_0 = \varepsilon_\infty \omega_{\text{LO}}^2/\omega_{\Gamma}^2 \) is the low-frequency dielectric constant of the lattice, including the contribution from the optic-phonon modes. The result is

\[ \mu = \frac{m^* e^2}{\pi \hbar^2 k_F \varepsilon_0} \ln \left(1 + \frac{3\pi \hbar^2 k_F \varepsilon_0}{2m^* e^2} \right) . \] (13)
Substitution of this value of $\mu$ into Eq. (11) yields the renormalized Coulomb parameter that we shall use in the next section to estimate the superconducting transition temperature for Ba-K-BiO. We shall then see that this superconductor is in a strong-coupling regime.

3. Results and discussion

In the calculation of the superconducting state properties of Ba$_{0.8}$K$_{0.4}$BiO$_3$, realistic values of some of the physical parameters can be obtained from experimental data. In particular, the effective mass $m^*$ of the carriers is obtained as $m^* = 2.4 \, m_e$ from the jump $\Delta C$ in the specific heat at $T_c$ [25],

$$m^*/m_e = 0.604 \sqrt[3]{\lambda L(0)} \left[ \frac{\Delta C}{(V_n T_c)} \right]^{3/4}.$$  \hspace{1cm} (14)

The value of $\Delta C/ T_c$ is given as 2.2 mJ / (mol K$^2$) from specific heat measurements [26], while the London penetration depth at zero temperature is $\lambda L(0) \equiv 3500$ Å from optical reflectivity data [27] and $V_n = 79$ Å$^3$ is the volume per formula unit.

Hence, the McMillan electron-phonon coupling strength $\lambda$ [28] is obtained as

$$\lambda = [m^*/m_e] - 1 \approx 1.4.$$  \hspace{1cm} (15)

From magnetization measurements [29] the value of the coupling constant is $\lambda = 0.9 - 1.1$, while tunnelling experiments [9,10] give $\lambda = 1.2 \pm 0.2$. The energy gap parameter $\beta$ is another measure of the electron-phonon coupling strength. The observed value [10,11, 13] of $\beta (~ 3.5-3.8$, close to the BCS value of 3.52) suggests that $\lambda$ is near to unity. The calculation of thermodynamic properties of Ba$_{0.7}$K$_{0.3}$BiO$_3$ [30] in terms of the Eliashberg theory yields $\lambda = 1.18$. Therefore, $\lambda = 1.4$ is a reasonable value and this superconductor is in a strong coupling regime.

A charge carrier density $n \approx 5.1 \times 10^{21}$ cm$^{-3}$ at $x \approx 0.4$ is estimated from Hall effect measurements [31]. The other parameters of the carriers are the Fermi velocity $v_F \approx 2.55 \times 10^7$ cm/s and the Fermi energy $\varepsilon_F \approx 0.45$ eV. Turning to the parameters related to the ions, a reasonable value of the background dielectric constant $\varepsilon_\infty$ in Bi oxides is $\varepsilon_\infty \approx 3$ [13,20,27]. The optic-mode frequencies, on the other hand, are taken from the inelastic neutron scattering measurements [8] as $\omega_{LO} \approx 564$ cm$^{-1}$ and $\omega_{TO} \approx $
500 cm\(^{-1}\). The estimated value of the static dielectric constant of the lattice then is \(\varepsilon_0 \equiv 3.82\).

With the above values for the input parameters, the upper and lower mode frequencies \(\hbar\Omega_+\) and \(\hbar\Omega_-\) are then estimated. The plasmon energy from Eq. (8) is estimated as 1.6 eV at \(2k_F\) and the frequency of the optical phonon is about 67 meV. X-ray photoemission and reflectance spectroscopy of Ba\(_{0.6}\)K\(_{0.4}\)BiO\(_3\) reveals a carrier plasmon at an energy of 1-2 eV [19,20]. The effective dynamic interaction corresponding to the above values of the system parameters is illustrated in Figure 1 as a function of frequency in a semi-logarithmic plot. A first pole at \(\omega = \Omega_-\) arises from the optical phonon and a second lies at \(\omega = \Omega_+\) in correspondence with the plasmon energy. The effective potential is attractive in the ranges \(\omega < \Omega_-\) and \(\Delta_2 < \omega < \Omega_+\), while it is repulsive in the domains \(\Omega_- < \omega < \Delta_2\) and \(\omega > \Omega_+\).

Finally, we evaluate the \(2k_F\) scattering of the carriers on the Fermi sphere. We find \(\mu = 0.80\) from Eq. (13) and \(\mu^* = 0.32\) from Eq. (11). The large reduction of \(\mu^*\) relative to \(\mu\) is due to the fact that the ratio \(\varepsilon_F / \hbar\omega_{LO}\) is much larger than unity. In conventional metals \(\mu^*\) is of order 0.10 to 0.13. The enhancement of \(\mu^*\) is attributed to the large values of the effective mass of the carriers and of the high-frequency dielectric constant. The carriers in the \(s\)-wave Ba-K-BiO superconductor move in a correlated way: this quenches the Coulomb repulsion and leads to an attractive interaction via exchange of coupled phonon and plasmon excitations.

We proceed to evaluate the transition temperature \(T_c\) for Ba-K-BiO. In the regime \(\lambda > 1\) the strong coupling theory applies [32], yielding

\[
T_c = 0.25 \omega_{LO} \left[ \exp \left( \frac{2}{\lambda_{\text{eff}}} \right) - 1 \right]^{-1/2} \tag{16}
\]

where

\[
\lambda_{\text{eff}} = (\lambda - \mu^*) \left[ 1 + 2\mu^* + \lambda \mu^* t(\lambda) \right]^{-1} \tag{17}
\]

and \(t(\lambda) = 1.5 \exp (-0.28\lambda)\). We find \(\lambda_{\text{eff}} \approx 0.52\) and \(T_c \equiv 30\) K, in agreement with the measured values \(T_c = 28 - 32\) K in Ba\(_{0.6}\)K\(_{0.4}\)BiO\(_3\) [1].
The isotope effect exponent is defined by $T_c \propto M^\alpha$, where $M$ is the ionic mass. Since the shift $\Delta T_c$ induced by isotopic substitution is small compared to $T_c$, the exponent $\alpha$ can be written as $\alpha = -\frac{M \Delta T_c}{(T_c \Delta M)}$. It is given by [33]

$$\alpha = \frac{1}{2} \left\{ 1 - \frac{\mu^*}{\lambda_{\text{eff}} \left[ 1 - \exp \left( -\frac{2}{\lambda_{\text{eff}}} \right) \right]} \left[ \frac{1}{\lambda - \mu^*} + \frac{2 + \lambda t (\lambda)}{3 + \lambda t (\lambda)} \right] \right\},$$

and hence we find $\alpha_0 = 0.33$ for oxygen in Ba-K-BiO. As already noted in section 1, the values of $\alpha_0$ from experiment cover a wide range. The present model predicts a reduction of the isotope-effect exponent in Ba-K-BiO relative to the BCS value for conventional superconductors, as a consequence of the unconventional plasmon-optical phonon pairing mechanism that we have treated.

Finally, the reduced energy gap parameter $\beta$ [34] is obtained from

$$\beta = 2\Delta(0) / [k_B T_c] = 3.52 \left[ 1 + 5.3 \left( \frac{T_c}{\omega_{\text{LO}}} \right)^2 \ln \left( \frac{\omega_{\text{LO}}}{T_c} \right) \right]$$

where $\Delta(0)$ is the energy gap at $T = 0$ K. We find $\beta = 3.6$, in agreement with the values reported from experiment and from band structure calculations as already discussed in section 1.

4. Conclusion

Addition of monovalent metal K at the divalent Ba site in BaBiO$_3$, which can be viewed as an ionic solid, introduces holes as current carriers. In this work we have treated the pairing mechanism for superconductivity in such a 3D cubic perovskite material as arising from Coulomb interactions screened by optical phonons and by plasmons. The main focus has been on relating the model to physical parameters of the superconducting state, i.e. the transition temperature $T_c$, the isotope-effect exponent $\alpha_0$ and the energy gap ratio $\beta$.

The model dielectric function $\varepsilon(q,\omega)$ that we have evaluated accounts for screening of the Coulomb repulsions by means of the RPA forms of the polarizabilities of the ionic lattice and of the gas of carriers. The plasmon-optical phonon mechanism yields a superconducting state in the strong coupling regime. The calculated value of the plasma frequency at $2k_F$ is in the range of values obtained from...
X-ray photoemission and reflectance spectroscopies. The renormalized Coulomb repulsion parameter \( \mu^* \) is large relative to conventional metals. The large enhancement of the effective mass of the carriers from plasmon-optical phonon coupling and the appreciable value of \( \mu^* \) lead to a value of \( T_c \) in agreement with observation. The evaluation of the isotope effect exponent and of the energy gap ratio also indicates that Ba-K-BiO can be considered as a strong-coupling superconductor.

In conclusion, superconductivity in \( s \)-wave \( \text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3 \) is successfully explained by a combined plasmon-optical phonon pairing mechanism.

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References


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[33] A. Bill, V. Z. Kresin, and S. A. Wolf, in Pair Correlations in Many-Fermion
    Solid State (1966) 265].
Figure 1. Effective dynamic interaction potential $V(q,\omega)$ at $q = 2k_F$ as a function of $\omega$ (in eV) on a semi-logarithmic scale. The two poles lie at frequencies $\Omega_-$ and $\Omega_+$, with $\Omega_- = 67$ meV and $\Omega_+ = 1.6$ eV in the present case of the Ba$_{0.6}$K$_{0.4}$BiO$_3$ superconductor.