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COMPUTATION OF EFFECTIVE ELECTRON-PHONON RELAXATION TIMES IN A HIGH T_c SUPERCONDUCTOR USING THE MEASURED TRACK RADII

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As a rule, charged particle tracks are able to act as vortex pinning centers in high-T_c superconductors and to improve the critical current density of materials. Despite a practical importance of this treatment, no satisfactory theory of track formation in high-T_c superconductors exists up to now. In our opinion, the thermal spike model (TSM) is the most appropriate one among other available models. G. Szenes proposed a phenomenological description based on the thermal spike concept which was successfully used to explain the evolution of track sizes with energy deposition for irradiated *Y-Ba-Cu-O* and *Bi-Sr-Ca-Cu-O* superconductors [1]. This approach contains some parameters totally independent on the physical properties of materials and can be only considered as a useful preliminary investigation of the problem. To the best of our knowledge, a more detailed consideration based on a system of coupled equations for electron and atom systems has never been employed for these materials.

The aim of the this paper is to check the conclusion of [1] that track formation in a $YBa_2Cu_3O_{7-\delta}$ superconductor is caused by extreme thermal processes which lead to the creation of an amorphous cylindrical region. To this end, the effective times τ of electron-atom energy relaxation are determined as fitting parameters for each pair of the measured track radii and energy deposition dE/dx (using other thermodynamic properties of the material known from independent experiments). To verify a self-consistency of the theory, the calculated results are compared then with similar values determined in short pulse laser experiments.

The present consideration is essentially based on [2] in which the TSM was developed for some amorphous metals and semiconductors. As compared with [2], the following improvements of the model are proposed here: a) taking into account the dynamics of energy deposition in a more detailed form, b) a more accurate solution of the set of coupled nonlinear differential equations describing the space-time evolution of electron and atom temperatures (to simplify the problem, till now the spatial expansion of the electron energy was considered independently of the atoms' degrees of freedom [2]).

Since the electron-atom system is not in thermal equilibrium, evolution of electrons' and lattice temperatures, T_e and T_i, respectively, is governed by a set of

coupled nonlinear differential equations:

$$\rho C_e(T_e)\frac{\partial T_e}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[rK_e(T_e)\frac{\partial T_e}{\partial r}\right] - g(T_e - T_i) + A(r,t),$$

$$\rho C_i(T_i)\frac{\partial T_i}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[rK_i(T_i)\frac{\partial T_i}{\partial r}\right] + g(T_e - T_i),$$

where C_e, C_i and K_e, K_i are the specific heat and thermal conductivity for the electronic system and lattice, respectively, ρ the material density, g the electron-atom coupling, $A(r,t)$ the power brought on the electronic system, and r the radius in cylindrical geometry with the ion path as the axis.

Mathematical model of the power source $A(r,t)$ is described in [3]. An inaccuracy of the model recently revealed for distances $r < 1\ nm$ [4] can not influence sufficiently the results of calculations because of total energy deposition over the range of $r < 10\ nm$ in the refined model is nearly the same as in [3]. Thus, the initial space-time distribution of energy deposition on electrons (including its dependence on the projectile velocity) is taken into account by the formulated algorithm rather carefully. This is important in view of results of [5], where the projectile velocity influence on track formation was reported.

As the physical properties of the matter are temperature dependent (in particular, the phase transition at the melting temperature is considered), the system of differential equations can be solved only numerically. Assuming that the mean value of electron diffusivity $D_e = K_e/\rho C_e$ is nearly a constant value[1] of about 2 cm^2/s [2], the equation for electron temperature can be written in the form

$$\frac{\partial T_e}{\partial t} = D_e \triangle T_e - \frac{1}{\tau}(T_e - T_i) + \frac{A(r,t)}{\rho C_e(T_e)}, \tag{1}$$

where $\tau = \rho C_e/g$ is the effective electron-atom interaction time averaged over electron temperatures.

The equation for lattice temperature was approximated by an analogous expression:

$$\frac{\partial T_i}{\partial t} = D_i \triangle T_i + \frac{1}{\tau}\frac{C_e}{C_i}(T_e - T_i), \tag{2}$$

[1] A possible weak dependence of D_e on electron temperatures is taken into account below.

where the Dulong-Petit value, $C_i = 3.1\ J\ cm^{-3}\ K^{-1}$, was taken for lattice specific heat. The other parameters of $YBa_2Cu_3O_{7-\delta}$ and the references used for their estimation are reported in Table I.

Table I

Parameter	Value	Source
ρ	$6.39\ g\ cm^{-3}$	[2]
K_i	$5.6\ 10^{-2} J\ (s\ cm\ K)^{-1}$	[6 – 10]
$\rho C_e \approx \gamma T_e$	$\gamma \approx (1.5 \pm 0.5) 10^{12}\ keV\ cm^{-3}\ K^{-2}$	[11]
Heat of melting	810±5 kJ mol^{-1}	[12]

It worth noting that significant experimental uncertainties for C_e (see Table I) have no strong influence on the result of lattice temperature calculations. Indeed, the total energy per unit volume contained in the electron subsystem is

$$Q(T_e) = \int_{T_0}^{T_e} C_e(T_e) dT_e \simeq \frac{C_e(T_e) T_e}{2}.$$

At the beginning of the energy relaxation process, $T_e \gg T_i$. Therefore, $C_e(T_e - T_i) \approx 2Q(T_e) = k\ dE/dx$ controlling a lattice temperature increase in eq. (2) does not depend on the inaccuracies of C_e.

The parameter τ in eqs. (1) - (2) was used to adjust the measured track radii R_{meas} in $YBa_2Cu_3O_{7-\delta}$ irradiated with ^{129}Xe ions for a beam energy of 1.3, 2.6 and 10 MeV/amu and with ^{208}Pb at 20 MeV/amu [14]. A scheme of adjustment and results are shown in Figs. 1 and 2, respectively[2]. The values of $T'_{melt} = 1283\ K$ and $T''_{melt} = 1573\ K$ in Fig. 1 correspond to the beginning and the end of melting in $YBa_2Cu_3O_{7-\delta}$ [13]. The heat of fusion was distributed in the melting temperature interval in accordance with the Gauss law (which is only an acceptable simplification of the true distribution) and added to the thermal capacity.

To estimate the proximity of the obtained results to the available theoretical and experimental data, let us turn to the Allen theory [16] which predicts an approximate linear dependence of τ on T_e:

[2]Details on the numerical solution of system (1) - (2) are published elsewhere [15].

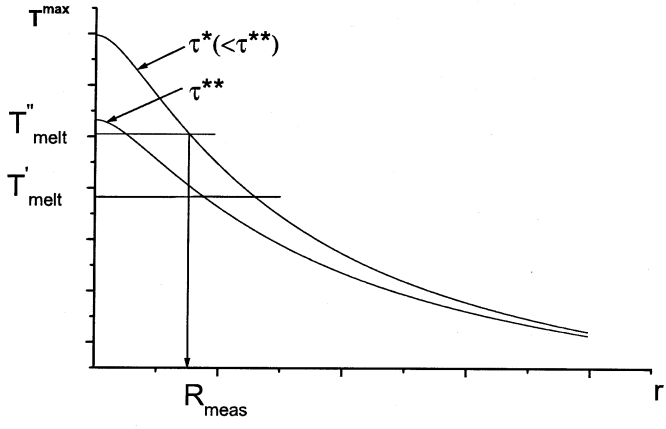

Fig. 1: Dependence of maximum lattice temperature T^{max} on the distance from the track center at different values of parameter τ and fixed dE/dx. According to the TSM, the track radius is restricted by the melted region, $T^{max} \geq T_{melt}$.

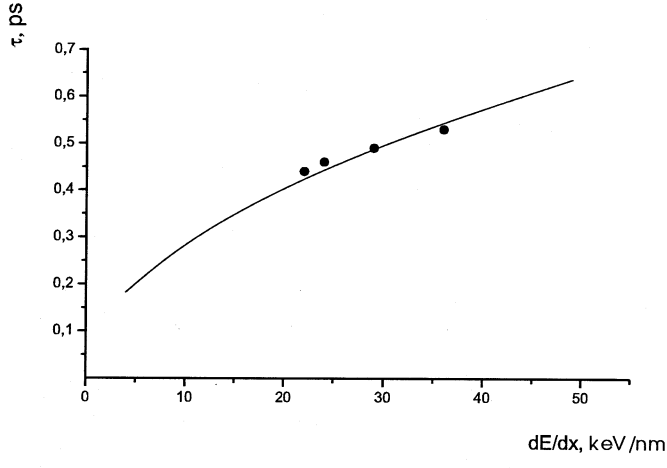

Fig. 2: Effective electron-atom relaxation time τ vs dE/dx. The points describe the model adjustment to the experimentally measured track radii; the curve is their approximation by the formula $\tau = \beta(dE/dx)^{1/2}$, where $\beta = 9.1 \cdot 10^{-14} s\ nm^{1/2} keV^{-1/2}$.

$$\tau_a \simeq \frac{\pi}{3}\frac{k_B}{\hbar\lambda < \omega^2 >}T_e.$$

In accordance with the experiment [17], $\lambda < \omega^2 >= 475 \pm 30\ meV^2$ for $YBa_2Cu_3O_{7-\delta}$. Therefore,

$$\frac{\tau_a}{T_e}(YBCO) \simeq (1,2 \pm 0,1) \cdot 10^{-16}\ s\ K^{-1}. \tag{3}$$

As far as $\rho, g \simeq const$, the TSM predicts the same linear dependence:

$$\tau = \rho C_e/g = \frac{\rho\gamma}{g}T_e.$$

The value of electron-atom coupling g which corresponds to [16] and [17] is equal to

$$g(YBCO) \simeq (2,4 \pm 0,9) \cdot 10^{12}, \frac{J}{cm^3 K s}.$$

Energy deposition dE/dx in Fig. 2 can be readily expressed through electron temperature T_e if one takes into account an estimate holds for any time t [2]

$$T_e(r) \simeq T_e(0)\exp(-r^2/4r_e^2(t)),$$

where the parameter r_e is almost independent[3] of dE/dx [2]. For $t = \tau$, it can be interpreted as the size of the excited electron cloud at the very end of the electron-atom relaxation process

$$r_e(\tau) \simeq r_0 + \sqrt{D_e\tau}.$$

Here r_0 is the half width of the initial radial distribution of energy deposition. For example, for amorphous metals and semiconductors, r_0 was found to be $1.5 \div 5\ nm$ and $r_e \simeq 14 \div 19\ nm$ [2].

Now one can estimate an electron temperature in the track center making use of the relation:

$$\frac{dE}{dx} = \int_0^\infty \frac{C_e(T_e)T_e}{2} 2\pi r \times 1\ dr = V\gamma T_e^2(0),$$

where $V = \pi r_e^2 \times 1$ is the effective cylinder volume containing excited electrons. The value of τ is proportional to $T_e(0)$ and, hence, to $(dE/dx)^{1/2}$.

[3]This assumption is consistent with Fig.2 if one supposes a small decrease of D_e with increasing T_e. The same conclusion for $D_e(T_e)$-dependence in the considered temperature interval was drawn in [17].

If one assumes for γ its mean experimental value (see Table I) and $r_e \simeq 18\ nm$ for $r_e(\tau)$ (this parameter approximately corresponds to the obtained estimations for r_0, D_e and τ), then eq. (3) following from Allen's theory [16] and the existing experimental data [17] is in full agreement with the curve shown in Fig. 2. One can see that the value of $r_e(\tau)$ is also close to the estimates of this parameter for amorphous metals and semiconductors [2]. Under the stipulated conditions, the electron temperatures in the track center at $t \simeq \tau$ are approximately equal to 4000 K.

It is readily seen that values of $r_e(t)$ on the time scale $(\tau/3 \div \tau)$ are significantly greater than the observed track radii $R_{meas} = 1.3 \div 3.5\ nm$ [14]. This means that for these times, electrons in the region $r \leq R_{meas}$ get cold mainly due to electron-atom relaxation. Similar conditions (i.e. cooling at the boundary is not important) are realized in experiments with laser femtosecond irradiation of materials. The experimentally obtained value of effective electron-atom relaxation time τ in $YBa_2Cu_3O_{7-\delta}$ is equal to $\tau = 0.06 \pm 0.01$ for $T_e = 410 \pm 60\ K$ [17]. Electron-phonon relaxation throughout a wide spectral range of pump laser pulses and $T_e \simeq 2500\ K$ was also studied in [19]. Time relaxation τ was found to vary from 0.1 to 0.9 ps for photon energies over an interval of $1.8 \div 2.2\ eV$. Both results are in good agreement with the curve shown in Fig. 2.

Summarizing, we conclude that the TSM gives rather a realistic explanation of track formation in high-T_c $YBa_2Cu_3O_{7-\delta}$. This conclusion is consistent with the other results obtained for this superconductor [6 - 12] and with the analysis of [1].

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Расчет эффективных электрон-фононных времен релаксации в высокотемпературном сверхпроводнике на основе измеренных радиусов треков

В модели теплового пика проведены расчеты процессов релаксации энергии, выделившейся при прохождении быстрых ионов в монокристалле высокотемпературного сверхпроводника $YBa_2Cu_3O_{7-\delta}$. Для каждой пары измеренных величин (радиусов треков и соответствующих тормозных способностей dE/dx ионов) определялось в качестве подгоночного параметра эффективное время τ электрон-атомной энергетической релаксации. Найдена зависимость этой величины от dE/dx в интервале $20 \div 40$ кэВ/нм. Результаты подгонки сравниваются с экспериментальными данными, полученными при помощи коротких лазерных импульсов на таком же материале, и с теорией Аллена, предсказывающей приблизительно линейный рост величины τ в зависимости от температуры электронов.

Работа выполнена в Лаборатории высоких энергий и в Лаборатории информационных технологий ОИЯИ.

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Computation of Effective Electron-Phonon Relaxation Times in a High T_c Superconductor Using the Measured Track Radii

Energy relaxation processes after fast heavy ions passage through $YBa_2Cu_3O_{7-\delta}$ single crystal have been calculated. Effective times τ of electron-atom energy relaxation have been determined as fitting parameters for each pair of the measured track radius and the value of dE/dx. The latter quantity has been chosen over the interval of $20 \div 40$ keV/nm. The calculated results are compared with short pulse laser experiments and with Allen's theory, which predicts almost a linear dependence of τ on electron temperature.

The investigation has been performed at the Laboratory of High Energies and at the Laboratory of Information Technologies, JINR.

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