

ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ
ДУБНА

E8-86-103

M.Koláč, B.S.Neganov, A.Sahling, S.Sahling

**LONG-TIME TUNNELING
IN AMORPHOUS METALS
AT HELIUM TEMPERATURES**

Submitted to
"Journal of Low Temperature Physics"

1986

1. Introduction

Very-long-time heat relaxation at low temperatures was observed in several amorphous dielectrics, e.g., in vitreous silica^{/1-4/}, PMMA^{/5,6/}, and in various other organic materials^{/4/}. Since such relaxation is understood in the terms of phenomenological tunneling model^{/7,8/}, it may be a common feature of all amorphous materials, i.e., also of metallic glasses. Then we would be able - measuring the heat release - to determine the density of the two-level states even for metals in normal state, where the heat capacity measurements are of little use because of the electron term.

Concerning amorphous metals, heat release measurements have been performed with superconducting LaZn only^{/9/} up to now. Heat release observed was about a hundred times larger than in vitreous silica probably due to the ortho-para conversion of hydrogen admixtures, and with this thermal background, power due to the tunneling was not seen. Indeed, the heat capacity measurements with superconducting metals^{/10,11/} and with vitreous silica^{/12-14/} show that the densities of the tunneling states in those materials do not differ essentially; the heat release should therefore be of the same order.

In this work, the results of the heat relaxation experiments with two metal glasses are presented. Some of the preliminary results have already been published in Ref. 15.

2. Theory

Many low-temperature ($T \ll 1K$) features typical of amorphous solids in contrast to the crystalline materials may be explained with the phenomenological tunneling model^{/7,8/}. According to this model, localized two-level systems characterized by quantum mechanical tunneling through the potential barrier between two wells exist in glasses. The parameters of each two-level system are asymmetry energy Δ , barrier energy V_B , well separation d , tunneling coupling energy $\Delta_0 = \hbar \omega_0 \exp(-\lambda)$, where $\hbar \omega_0$ is the zero point energy either well, and the tunneling parameter $\lambda = d(2mV_B)^{1/2}/\hbar$ (m is the mass of the tunneling object). The energy splitting between the two lowest states in the two wells is $E = (\Delta^2 + \Delta_0^2)^{1/2}$.

To explain the time-dependent specific heat term, approximately proportional to T , observed in glasses, in the framework of tunneling model, the distribution function of two-level systems $P(\Delta, \lambda)$ does not need actually to depend on Δ and λ . For small values of Δ and λ , contributions of which manifest itself for $T \ll 1K$ and short measuring times, an assumption of uniform distribution is reasonable, namely

$$P(\Delta, \lambda) = \bar{P} = \text{const.} \quad (1)$$

This gives a time-dependent density of states^{/7,8,16,17/}

$$n(E, t) = n_0(t) = (\bar{P}/2) \ln(4t/\tau_{\min}) \quad (2)$$

and the corresponding contribution to the specific heat

$$c_t = (\pi^2 k_B^2 / 12) T \bar{P} \ln(4t/\tau_{\min}), \quad (3)$$

where k_B is the Boltzmann number, and τ_{\min} is the shortest relaxation time. As a result, heat release appears after cooling the system from the equilibrium temperature T_1 to the temperature T_0 ,

$$\dot{Q} = V \int_{T_0}^{T_1} (dc/dt) dT; \quad (4)$$

with the uniform distribution (1), we have from (3)

$$\dot{Q}(T_1, T_0, t) = V (\pi^2 k_B^2 / 24t) (T_1^2 - T_0^2) \bar{P}, \quad (5)$$

where V is the volume of the specimen.

Equations (2), (3) and (5) hold for small values of E only. Because of the finite number of tunneling particles, the density of states $n(E, t)$ should fall to zero for large E . To take this fact into account, calculations of c_t and \dot{Q} were performed using

$$n(E, t) = n_0(t) / (1 + \exp((E - E_f)/k_B T_b)), \quad (6)$$

where $E_f = k_B T_f$ and T_b are constant; $k_B T_b$ is the "width" of the transient region. For $T_b/T_f \rightarrow 0$, (6) transforms into

$$\begin{aligned} n(E, t) &= n_0(t) & \text{for } E \leq E_f, \\ n(E, t) &= 0 & \text{for } E > E_f. \end{aligned} \quad (7)$$

Usually, maximum value of E has been connected with maximum value of barrier height V_{\max} , and $V_{\max} \approx k_B T_g \approx 0.1$ eV (T_g is the glass temperature) was assumed^{/7,17/}. Then (1) should hold well at helium temperatures. We shall see this is not true for our specimen, where $E_f \ll k_B T_g$.

With distribution (6), we get - instead of (3) -

$$c_t = (\pi^2 k_B^2 / 12) \bar{P} I_1(T/T_f, T_b) \ln(4t/\tau_{\min}), \quad (8)$$

where

$$I_1(T/T_f, T_b) = (6/\pi^2) \int_0^{\infty} \frac{x^2 \exp(-x) dx}{(1 - \exp(-x))^2 (1 + \exp((xT/T_f - 1)/(T_b T_f)))} \quad (9)$$

and - instead of (5) -

$$\dot{Q}(T_1, T_0, t) = (\pi^2 k_B^2 / 24t) PV (I_2(T_1/T_f, T_b) T_1^2 - I_2(T_0/T_f, T_b) T_0^2), \quad (10)$$

where

$$I_2(T/T_f, T_b) = 2(T_f/T)^2 \int_0^{T/T_f} (T/T_f) I_1(T/T_f, T_b) d(T/T_f). \quad (11)$$

Finite number of tunneling particles makes us also introduce the maximum tunneling parameter λ_{\max} ; and a corresponding maximum relaxation time τ_{\max} ; then for $t \geq \tau_{\max}$ (2), (3) and (5) are incorrect.

After cooling the specimen sufficiently fast from T to $T_0=0$, excited tunneling particles relax and the total energy ξ of the system decreases according to

$$\xi(T, 0, t) = \sum_{i=1}^N \xi_i(T, 0) \exp(-t/\tau_i), \quad (12)$$

where $\xi_i(T, 0)$ is the sum of the excitation energies at T of all levels with relaxation time τ_i ; N is the total number of various relaxation-time values. Transition from the sum of the integral gives

$$\xi(T, 0, t) = \int_{\tau_{\min}}^{\tau_{\max}} f(T, 0, \tau) \exp(-t/\tau) d\tau, \quad (13)$$

where $f(T, 0, \tau)$ is proportional to the relaxation time distribution function $P(\tau)$. Since $\tau \sim \exp(2\lambda)$, $P(\tau) = (P/2\tau)$ follows from $P(\lambda) = \bar{P}$. Writing

$$f(T, 0, \tau) = a(T)/\tau, \quad (14)$$

we get from (13), (14)

$$\dot{Q} = \partial \xi / \partial t = a(T) \cdot t^{-1} (\exp(-t/\tau_{\max}) - \exp(-t/\tau_{\min})). \quad (15)$$

Expression (15) really yields a usual t^{-1} dependence of $\dot{Q}(t)$ for $t \ll \tau_{\max}$. For $t > \tau_{\max}$, this dependence transforms into an exponential one. Comparing (15) with (10), we obtain

$$a(T) = (V \pi^2 k_B^2 / 24) \bar{P} I_2(T/T_f, T_b) T^2. \quad (16)$$

Then in a more general case, the heat release after rapid temperature variation from T_1 to T_0 (cooling when $T_1 > T_0$, heating when $T_1 < T_0$;

$T_0, T_1 > 0$), equals (for $t \gg \tau_{\min}$)

$$\dot{Q}(T_1, T_0, t) = (a(T_1) - a(T_0)) t^{-1} \exp(-t/\tau_{\max}). \quad (17)$$

All expression we have written for $\dot{Q}(T_1, T_0, t)$ are valid, if the thermal equilibrium was established before the cooling (heating) at T_1 . Let us see what power is to be released when, after relaxation is completed at T_0 , the specimen is heated up to the temperature T_H , and after the time t_H cooled to T_0 again. The corresponding heat release will be

$$\dot{Q}(T_H, T_0, t_H, t) = \int_{\tau_{\min}}^{\tau_{\max}} (a(T_H) - a(T_0)) \tau^{-2} (1 - \exp(-t_H/\tau)) \exp(-t/\tau) d\tau. \quad (18)$$

Usually, $\tau_{\min} \ll t \ll \tau_{\max}$, and

$$\dot{Q}(T_H, T_0, t_H, t) = (a(T_H) - a(T_0)) t^{-1} (1 + t/t_H)^{-1}. \quad (19)$$

Using (19), one can determine, how long t_H must be for reaching the "equilibrium" heat release (theoretically, $t_H \rightarrow \infty$). As a rule, $t_H = 20$ h in our experiments; the heat release 1 h after cooling differs from the equilibrium one by no more than 5 per cent.

It is interesting that the ratio of the power released for two different t_H and the same T_0 does not depend on T_H ; this is not difficult to prove experimentally.

3. Specimens and experiment

Two specimens were studied. Specimen I was a strip of amorphous ferromagnet $\text{Fe}_{80}\text{B}_{14}\text{Si}_6$ (produced in the Central Institute for Solid State Physics and Material Research of Acad.Sci., Dresden, GDR). Its length was 43.3 m, width 31 mm, thickness 40 μm . The strip was wound up into the form of a cylinder, 50 mm in diameter. Strips of copper foil (thickness 30 μm) were fixed at various places between the windings of $\text{Fe}_{80}\text{B}_{14}\text{Si}_6$ (total contact area $\sim 600\text{cm}^2$); a thermometer (germanium resistor), a heater and a contact for the heat switch were mounted on this copper foil. The mass of $\text{Fe}_{80}\text{B}_{14}\text{Si}_6$ was 288.18 g, that of the copper and resistors with negligible amount of the solder (no glue was used) equals 15.97 g. In such system, thermal equilibrium sets fairly fast throughout the specimen. Even under very unsuitable conditions, equilibrium was set in several tens of seconds.

Specimen II consisted of a strip of amorphous ferromagnet $\text{Co}_{69}\text{Fe}_{4.5}\text{Cr}_2\text{Si}_{2.5}\text{B}_{22}$ (of the same origin) with the length of 77.6 m, width 14.2 mm, and thickness 35 μm . The construction was almost the same as of specimen I, only specimen II consisted of two "floors"

because of the small width of the strip. The mass of $\text{Co}_{69}\text{Fe}_{4.5}\text{Cr}_2\text{Si}_{2.5}\text{B}_{22}$ was 250.3 g (124.4 g + 125.9 g), that of the copper 16.1 g.

The experimental arrangement was the same as in Ref. 19, 20. Specimen I (II) with the thermometer and the heater hangs in the calorimeter on 12 (8) kapron threads (0.13 mm in diameter, 31 mm long). The coupling constant A between specimen I (II) and the body of the calorimeter with the heat switch off was slightly temperature dependent, $A=122$ pW/mK (72 pW/mK) - i.e. about 10 pW/mK per one kapron thread - at 1.3K. The heat resistance of the closed switch was determined as 10^4 K/W at the same temperature.

The efficiency of the switch and all the contacts is demonstrated in Fig. 1, where time necessary for cooling the specimen from the temperature T_1 to 1.3K is shown.

The value of the thermal background power $\dot{Q}_B = (1150 \pm 50)$ pW was somewhat larger than in previous experiments. Since it increased after changing the radiation shields in the calorimeter central tube, we suppose \dot{Q}_B be largely due to the radiation along the suspension system. On the other hand, maximum variation of \dot{Q}_B in time, which limits the accuracy of measurement, was reduced to $\dot{Q}_B \lesssim 100$ pW.

During the measurements, heat capacities of both specimens were determined in the temperature range somewhat larger than necessary for the heat release calculations.

The heat release \dot{Q} and the specific heat release $\dot{q} = \dot{Q}/m$ (m is the mass of the amorphous metal) were calculated, as usual [19,20], from the drift of the specimen temperature with the heat switch off, corrected for the heat background \dot{Q}_B and heat leak \dot{Q}_A :

$$\dot{Q} = \dot{Q}_m - \dot{Q}_A - \dot{Q}_B, \quad (20)$$

where

$$\dot{Q}_m = \dot{R}C / (\partial R / \partial T), \quad (21)$$

$$\dot{Q}_A = A(T_K - T). \quad (22)$$

\dot{Q} is the measured power, \dot{R} is the germanium thermometer resistance drift, C is the heat capacity of the specimen, $\partial R / \partial T$ is the sensitivity of the thermometer; as a rule, $T_K \sim T$.

Fig.1. The time necessary for cooling the specimen in the calorimeter from T_1 to $T_0 = 1.3$ K.

1 - $\text{Fe}_{80}\text{B}_{14}\text{Si}_6$, 2 - $\text{Co}_{69}\text{Fe}_{4.5}\text{Cr}_2\text{Si}_{2.5}\text{B}_{22}$.

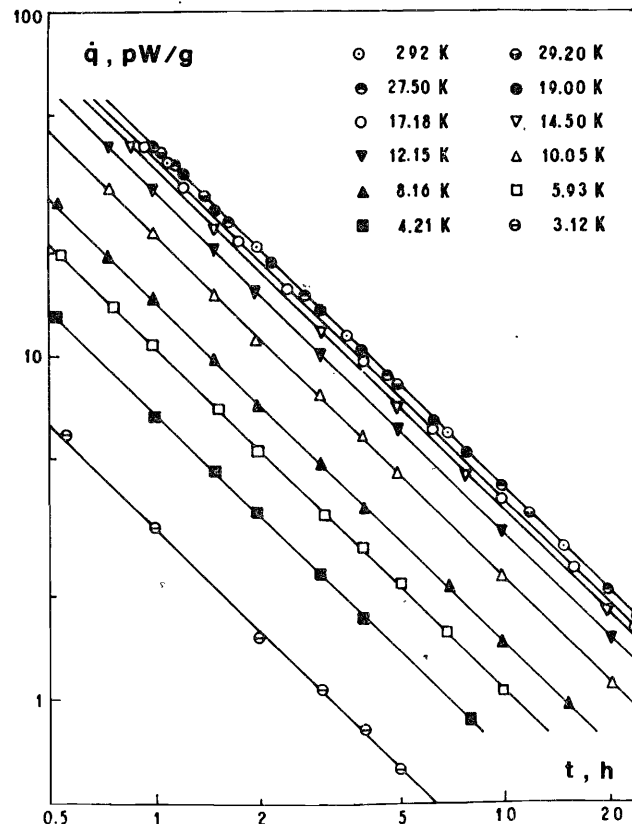
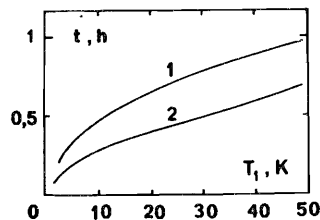


Fig. 2. The specific power released in specimen I ($\text{Fe}_{80}\text{B}_{14}\text{Si}_6$) after cooling from various T_1 ($3.12 \text{ K} \leq T_1 \leq 292 \text{ K}$) to $T_0 = 1.3 \text{ K}$ as a function of the time. Straight lines: $\dot{q} \sim t^{-1}$.

The results are presented as $\dot{q} = \dot{Q}/m$ - the power released in 1 g of the material under study.

At the beginning, the specimen was cooled from room temperature to 1.3K and the long-time power release $\dot{Q}(t)$ was measured, until it dropped to the level of background fluctuations (100 pW). Then the specimen was successively heated to T_1 ($3.12 \leq T_1 \leq 292 \text{ K}$) and kept for $t_H = 20$ hours at that temperature; after another cooling to 1.3K the time dependence of $\dot{Q}(t)$ was measured again. For some values of T_1 much less heating time was also used, $t_H = 0.2$ h and/or $t_H = 0.5$ h.

Fig. 3. The specific power released in specimen I 1 hour after cooling from T_1 to $T_0 = 1.3\text{K}$ as a function of $T_1^2 - T_0^2$. $\circ - t_H = 20\text{ h}$, $\bullet - t_H = 0.5\text{ h}$, $\triangle - t_H = 0.2\text{ h}$ (see the text); 1 - standard tunneling theory (5) with $\bar{P}_m = 2.3 \times 10^{37}/\text{Jg}$, 2 - equation (10) with $\bar{P}_m = 2.3 \cdot 10^{37}/\text{Jg}$, $T_f = 20\text{K}$, $T_b = 0$.

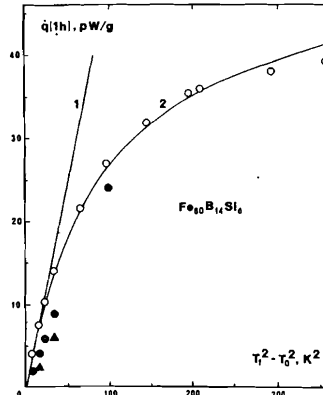
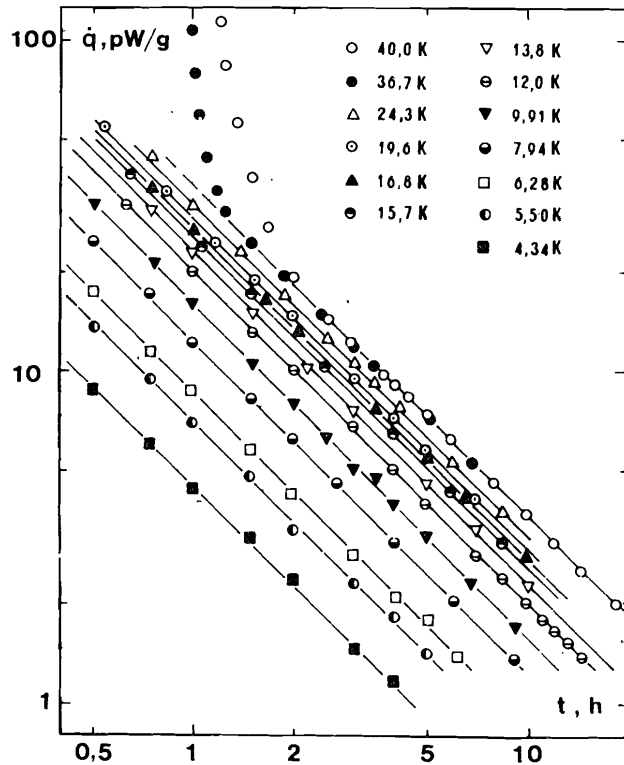


Fig. 4. The specific power released in specimen II ($\text{Co}_{69}\text{Fe}_{4.5}\text{Cr}_2\text{Si}_{2.5}\text{B}_{22}$) after cooling from various T_1 ($4.34\text{K} \leq T_1 \leq 40.0\text{K}$) to $T_0 = 1.3\text{K}$ as a function of the time. Straight lines $\dot{q} \sim t^{-1}$.



4. Results

For both specimens, heat release after cooling from any "heating" temperature T_1 is proportional to t^{-1} (Fig. 2,4). Deviations from the straight line just after the cooling for large T_1 are evidently due to unsufficiently rapid cooling (relaxation of levels with small E begins later) and to unfinished process of reaching the thermal equilibrium throughout the specimen at the beginning of the measurements. This is the case of the specimen II and $T_1 > 35\text{K}$ (see Fig. 4).

In Figs. 3,5 power release $\dot{q}(1\text{h}) = \dot{Q}(1\text{h})/m$ at $t = 1\text{h}$ after the cooling is shown as a function of $T_1^2 - T_0^2$ ($T_0 = 1.3\text{K}$). For small T_1 , long-time heat release increases with increasing T_1 ; it is almost independent of T_1 for large T_1 . Measured values of $\dot{q}(1\text{h})$ after short heating time t_H are also presented in Figs. 3,5.

5. Discussion

Ortho-para conversion in hydrogen bubbles, precipitated in the copper /18-20/ or in amorphous LaZn /9/, is well known as a source of a long-time heat release. But such heat release is not proportional to t^{-1} (the dependence is more complicated) and the dependence on T_1 is quite different: the heat release is about three

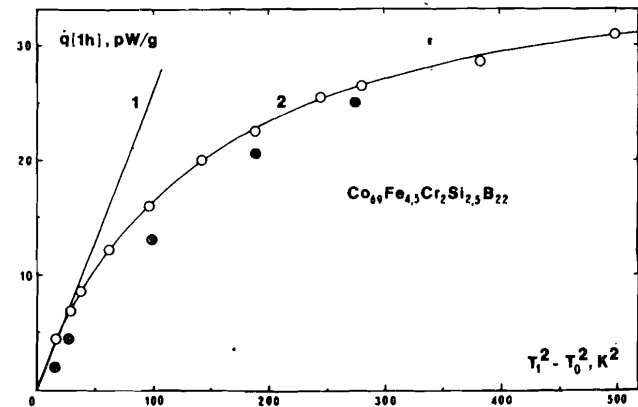


Fig. 5. The specific power released in specimen II 1 hour after cooling from various T_1 to $T_0 = 1.3\text{K}$ as a function of $T_1^2 - T_0^2$. $\circ - t_H = 20\text{ h}$, $\bullet - t_H = 0.5\text{ h}$, (see the text); 1 - standard tunneling theory (5) with $\bar{P}_m = 1.2 \cdot 10^{37}/\text{Jg}$, 2 - equation (10) with $\bar{P}_m = 1.2 \times 10^{37}/\text{Jg}$, $T_b = 0$.

orders of magnitude more intensive after cooling from room temperature than that from 30K. In this experiments, the heat release after cooling from 30K does not differ significantly from the heat release after cooling from room temperature. Moreover, our measured heat release is of the same order as that in vitreous silica ^{/4/}. Thus, the possible heat release due to the hydrogen ortho-para conversion in the copper and/or glass itself can be neglected.

Deviations from the t^{-1} law were not found for any t until $Q \lesssim Q_D$. Thus the relaxation time spectrum extends over 100 h ($\tau_{\max} > 100$ h) for our specimens, regardless the essential difference between metals and dielectrics - the presence of conduction electrons. The absence of conduction-electrons influence may be due to a rather high measuring temperature, $T_0 = 1.3K$.*

The proportionality $\dot{Q} \sim (T_1^2 - T_0^2)$ for small T_1 enables to determine the parameter $\bar{P}_m = \sqrt{E}/m$ from (5): $\bar{P}_m = (2.3 \pm 0.2) 10^{37}/Jg$ for the specimen I and $\bar{P}_m = (1.2 \pm 0.1) 10^{37}/Jg$ for the specimen II. Analogous measurements with vitreous silica yielded $\bar{P}_m = 4.5 \cdot 10^{37}/Jg$ ^{/4/} and $1.5 \cdot 10^{38}/Jg$ ^{/2,3/} in good agreement with the results from heat capacity ($2.4 \cdot 10^{38}/Jg$ ^{/12-14/}, heat conductivity ($1.7 \cdot 10^{38}/Jg$ ^{/13,22,23/}) and ultra-sound ($9.5 \cdot 10^{37}/Jg$ ^{/24/}) measurements. Our slightly reduced values of \bar{P}_m seem reasonable taking into account lower than in vitreous silica tunneling contribution to the heat capacity in the case of amorphous superconductors (ZrCu ^{/11/}).

Thus, the heat release studies enable one to find the two-level systems distribution function $P(\Delta, \lambda)$ even for metals in normal state; it is so far the only method to fix P_m directly without any other experimental data.

Our results for higher initial temperatures T_1 can hardly be explained with the standard tunneling model with $P(\Delta, \lambda) = \bar{P}$; the same was found for vitreous silica ^{/4/}. On the other hand, the data calculated from distribution (7) are in good agreement with our experimental results if we take $\bar{P}_m = 2.3 \cdot 10^{37}/Jg$, $T_f = 20K$ and $T_b = 0$ for specimen I (Fig. 3), and $\bar{P}_m = 1.2 \cdot 10^{37}/Jg$, $T_f = 24K$ and $T_b = 0$ for specimen II. Assuming distribution (7) for vitreous silica,

* If we assume that the relaxation time due to the interaction with the conduction electrons at 10 mK $\tau_e \approx 10^{-4} \tau_p$ ^{/21/}, where τ_p is the relaxation time due to photon interaction, and $\tau_e/\tau_p \sim E^2/16, 17, 21/$, then $\tau_e > \tau_p$ at $T = 1.3K$, and in relaxation of the levels with $E/k_B > 1.3K$ the influence of the conduction electrons is probably negligible.

values $\bar{P}_m = 4.5 \cdot 10^{37}/Jg$, $T_f = 13K$, $T_b = 0$ well agree with experiments ^{/3,4/}. *

The experimental values of E_f are surprisingly much smaller, than $k_B T_g$ where the glass temperature T_g is probably near to the recrystallization temperature in metal, $\sim 640K$ ($\geq 690K$) for specimen I (II). Indeed, $T_f \approx T_g/30$ for both our specimens. Maybe, even the maximum barrier height is much smaller than the characteristic glass energy $k_B T_g$? If this is the case, the tunneling parameter λ may not be temperature independent except for $T_0 \ll T_f$; for higher temperatures, the dependence λ on T_0 and t may be more complicated than according to (10) and (19).

Because of large heat capacity of metallic glasses, the measurements at higher temperatures were not performed. But deviations from (19) were actually observed.

In Fig. 6 the ratio $\dot{q}(t_H, 1h)/\dot{q}(1h)$ is shown as a function of T_H/T_f ; $\dot{q}(t_H, 1h)$ is specific power released 1 hour after the cooling from T_H , where the specimen (preliminary relaxed at T_0) stayed for the time t_H , and $\dot{q}(1h)$ is the specific power released 1 hours after

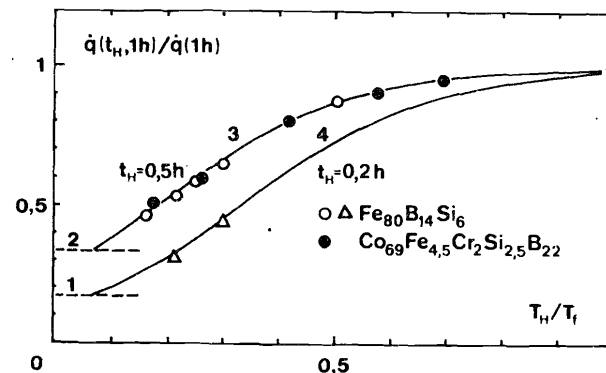


Fig. 6. The dependence of the value $\dot{q}(t_H, 1h)/\dot{q}(1h)$ on T_H/T_f , where $\dot{q}(t_H, 1h)$ is the specific power released 1 hour after cooling down from T_H for short heating times ($t_H = 0.2$ h or 0.5 h) and $\dot{q}(1h)$ is the same for long heating times ($t_H = 20$ h, $T_H = T_1$). Dashed lines - equation (19), full curves - equation (25) with $t=1$ h, $\alpha=6$, $T_f=20K$ ($24K$) for specimen I (II), $t_H = 0.2$ h (curve 1), $t_H=0.5$ h (curve 2).

* Calculations in ^{/3/}, resulting in $T_f = (4 \pm 2)K$ and $T_b \approx 10K$, are somewhat mysterious: using such values, even the condition $n(E, t) = n_0(t)$ for $E \ll E_f$ is not fulfilled.

the cooling from "equilibrium" $T_H = T_1$ (the specimen stayed at T_H for 20 hours). The dashed curves correspond to (19) with $t_H = 0.2$ h and $t_H = 0.5$ h. For larger T_H/T_f the ratio $\dot{q}(t_H, 1 \text{ h})/\dot{q}(1 \text{ h})$ increases for both specimen, which may be due to the drift of the time relaxation τ_i spectrum to shorter τ , since the heat relaxation at elevated temperatures is faster, than according to the standard theory.

If we assume the tunneling parameter λ' temperature dependent as

$$\lambda' = \lambda - (\alpha/2) \cdot T/T_f, \quad (23)$$

we get temperature dependence of the relaxation time ($\tau' \sim \exp(2\lambda')$) /16,17/

$$\tau' = \tau \cdot \exp(-\alpha T/T_f). \quad (24)$$

Then, according to (18) and for $\tau_{\min} \ll t \ll \tau_{\max}$

$$\dot{q}(T_H, T_0, t_H, t) / \dot{q}(T_H, T_0, t) = 1 / (1 + (t/t_H) \exp(-\alpha T_H/T_f) / \exp(-\alpha T_0/T_f)). \quad (25)$$

The agreement between the model and experiment is surprisingly good, when taking $t=1$ h and $\alpha=6$ for both $t_H = 0.2$ h (curve 4) and $t_H = 0.5$ h (curve 3).

Thus, the parameter T_f seems to control both the energy distribution of the two-level systems and the change of the relaxation time spectrum; maybe, T_f has a deeper physical meaning. It would be interesting to check the existence of such deviation from (19) in another glasses and possible degree of universality of (10) and (25) as functions of T_0/T_f and T_H/T_f . At higher T_0 (10) probably does not hold. Up to now, experiments with various T_0 have been performed for vitreous silica only, and only for $T_0 \ll T_f \approx 13\text{K}$ ($0.05\text{K} \leq T_0 \leq 1.08\text{K}$) /1,2,4/; here the results agree well with (10). We suppose that dielectrics are more convenient for possible measurements at higher T_0 .

6. Conclusions

Very-long time heat release observed in metallic glasses is similar to that in dielectrics; such heat release is probably a common feature of all amorphous materials. Experimental values of \bar{P}_m , calculated from measurements at sufficiently low temperatures, do not differ essentially both for our metallic specimens and vitreous silica /4/.

Standard tunneling model assumption $n(E, t) = n_0(t)$, i.e. $P(\Delta, \lambda) = \bar{P} = \text{const}$ is compatible with measured values for rather small values of E only. For higher E , long-time heat release in our specimens may

be explained by assuming $n(E \leq E_f, t) = n_0(t)$ and $n(E > E_f, t) = 0$, temperature $T_f = E_f/k_B$ being about thirty times lower than the recrystallization temperature.

At elevated temperatures, viz. $T_0 \geq T_f/10$, the relaxation time in the two-level systems probably depends on the temperature T_0 (higher T_0 , shorter relaxation time) in contrast to the standard tunneling model.

Because of small value of T_f , it would be not difficult to separate the tunneling and ortho-para conversion terms in the total power released, if necessary.

Acknowledgements

The authors are indebted to Prof. G. Lehmann and Dr. S. Roth for providing glassy metals for the study and for valuable discussions.

References

1. J. Zimmermann and G. Weber. Phys. Rev. Lett. **46**, 661 (1981)
2. M. T. Loponen, R. C. Dynes, V. Narayanamurti and J. P. Garno. Phys. Rev. B **25**, 1161 (1982)
3. M. Schwark. Berichte der Kernforschungsanlage Jülich - Nr. 1919, ISSN 0366-0885, Mai 1984
4. N. Schwark, F. Pobell, M. Kubota and R. M. Mueller. J. Low Temp. Phys. **58**, 171 (1985)
5. D. S. Greywall. Phys. Rev. B **18**, 2127 (1978)
6. J. Zimmermann. Cryogenics **24**, 27 (1984)
7. W. Anderson, B. I. Halperin and C. N. Varma. Phil. Mag. **25**, 1 (1972)
8. W. A. Phillips, J. Low Temp. Phys. **7**, 351 (1972)
9. A. Ravex and J. C. Lasjaunias. J. Low Temp. Phys., **48**, 159 (1982)
10. J. E. Gräbner, B. Golding, R. J. Schulz, P. S. L. Hsu and H. S. Cheu. Phys. Rev. Lett., **39**, 1480 (1977)
11. H. v. Lohneysen, M. Platte, W. Sander, H. J. Schink, G. v. Mimmigerode and K. Samwer. J. Physique **41**, C-8-475 (1980)
12. R. B. Stephens. Phys. Rev. B **13**, 852 (1976)
13. J. C. Lasjaunias, A. Ravex, M. Vandrope and S. Hunklinger. Solid State Commun. **17**, 1045 (1975)
14. J. Zimmermann and G. Weber. Phys. Lett., **86A**, 32 (1981)
15. M. Koláč, B. S. Neganov, A. Sahling, S. Sahling. to be published in Solid State Commun. (1985)
16. J. Jackle. Z. Phys. **257**, 212 (1972)
17. J. L. Black. Phys. Rev. B **17**, 2740 (1978)
18. M. Schwark, F. Pobell, W. P. Halperin, C. Buchal, J. Hanssen, M. Kubota and R. M. Mueller. J. Low Temp. Phys., **53**, 685 (1983)

19. M.Koláč, B.S.Neganov and S.Sahling. J.Low Temp.Phys. 59, 547 (1985); JINR E-8-84-460, Dubna, 1984
20. M.Koláč, B.S.Neganov, A.Sahling and S.Sahling. JINR E-8-85-404, Dubna, 1985
21. B.Golding, J.E.Graebner, A.B.Kaue and J.L.Black. Phys.Rev.Lett. 41, 1487 (1978)
22. R.C.Zeller and R.O.Pohl. Phys.Rev. B 4, 2029 (1971)
23. R.B.Stephens. Phys.Rev. B 8, 2896 (1973)
24. B.Golding, J.E.Graebner and R.J.Schultz. Phys.Rev.Lett. 14, 1660 (1970)

Received by Publishing Department
on February 21, 1986.

Колач М. и др.

E8-86-103

Медленное туннелирование

в аморфных металлах при гелиевых температурах

Измерялось медленно релаксирующее тепловыделение в аморфных $\text{Co}_{69}\text{Fe}_{4.5}\text{Cr}_2\text{Si}_{2.5}\text{B}_{22}$ и $\text{Fe}_{80}\text{B}_{14}\text{Si}_6$ после охлаждения от $T_1/3, 12\text{K} \leq T_1 \leq 292\text{K}$ до $T_0 = 1,3\text{K}$. Выделяемая мощность строго пропорциональна t^{-1} / $0,5 \text{ ч} \leq t \leq 60 \text{ ч}$ /. При низких T_1 результаты эксперимента хорошо согласуются со стандартной теорией туннелирования. Полученные плотности состояний двухуровневых систем очень близки плотности этих систем в кварцевом стекле. Для более высоких T_1 экспериментальное тепловыделение можно объяснить предположением о существовании максимальной энергии E_f в функции распределения.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1986.

Koláč M. et al.

E8-86-103

Long-Time Tunneling in Amorphous Metals
at Helium Temperatures

Long-time heat release in amorphous $\text{Co}_{69}\text{Fe}_{4.5}\text{Cr}_2\text{Si}_{2.5}\text{B}_{22}$ and $\text{Fe}_{80}\text{B}_{14}\text{Si}_6$ after cooling from T_1 ($3.12\text{K} \leq T_1 \leq 292\text{K}$) to $T_0 = 1.3\text{K}$ was measured. The power released is proportional to t^{-1} ($0.5 \text{ h} \leq t \leq 60 \text{ h}$). At low T_1 , the experimental results are in good agreement with the standard tunneling theory. The resulting densities of states of two-level systems are close to those in vitreous silica. For higher T_1 , observed heat release may be explained assuming the existence of a maximum energy E_f in the distribution function.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1986