Magnetic field dependent atomic tunneling in non-magnetic glasses

S. Ludwig [1], C. Enss, S. Hunklinger

Kirchhoff-Institut für Physik, Universität Heidelberg, D-69120 Heidelberg, Germany

Abstract

The low-temperature properties of insulating glasses are governed by atomic tunneling systems (TSs). Recently, strong magnetic field effects in the dielectric susceptibility have been discovered in glasses at audio frequencies at very low temperatures. Moreover, it has been found that the amplitude of two-pulse polarization echoes generated in non-magnetic multi-component glasses at radio frequencies and at very low temperatures shows a surprising non-monotonic magnetic field dependence. The magnitude of the latter effect indicates that virtually all TSs are affected by the magnetic field, not only a small subset of systems. We have studied the variation of the magnetic field dependence of the echo amplitude as a function of the delay time between the two excitation pulses and at different frequencies. Our results indicate that the evolution of the phase of resonant TSs is changed by the magnetic field.

Key words: amorphous solids; tunneling systems; coherent phenomena

At low temperatures the structural disorder in glasses causes low-energy excitations. In the phenomenological 'standard tunneling model' (STM) these excitations originate from the motion of groups of atoms between positions at almost equivalent energies [1,2]. The difference in depth of the wells is the asymmetry energy, while the overlap of the localized wave functions leads to the tunnel splitting. Both parameters are broadly distributed due to the randomness of the glassy structure.

While the STM described the thermal, elastic and dielectric properties of structural glasses consistently with experiments at low temperatures for almost 30 years, recent experiments revealed discrepancies mostly at temperatures below 100 mK. It has been proposed that the interaction between the tunneling systems is responsible for the observed deviations from the STM, which is based on the assumption that the tunneling systems are independent of each other [3–5]. Recently, an unexpected discovery was made, namely that non-magnetic glasses are sensitive to magnetic fields [6,7]. In particular, the dielectric constant of certain glasses shows a non-monotonic magnetic field dependence at audio frequencies. In addition, the amplitude of spontaneous polarization echoes exhibits a non-monotonic variation with magnetic fields [8]. The magnitude of the latter effect has led to the conclusion, that virtually all tunneling systems observed in the echo experiments contribute to the magnetic field dependence.

To explain these observations, it has been proposed that tunneling occurs in a three-dimensional potential landscape. In this case the tunneling motion of electrically charged particles leads to the flow of an electrical current in a closed loop, which is affected by magnetic fields [9,10]. To further investigate the coherent properties of tunneling states in magnetic fields we have carried out two-pulse echo experiments on the multi-component glass BK7. Fig. 1 shows the magnetic field dependence of the echo amplitude for two different frequencies (0.9 GHz and 4.6 GHz) and for two different delay times t_{12} between the two exciting microwave pulses (1.5 μs and 6 μs) plotted on a logarithmic field scale. As in case of the previously studied multi-component glass a-BaO-Al_2O_3-SiO_2, we find a

[1] E-mail: sludwig@stanford.edu
present address: Varian Physics Building, 382 Via Pueblo Mall, Stanford, CA 94305, USA

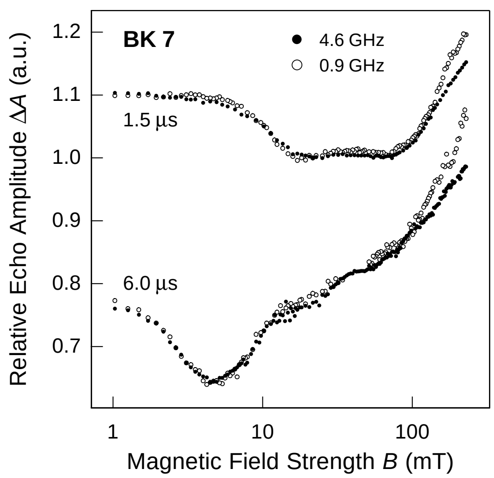

Fig. 1. Amplitude of two-pulse echoes generated in BK7 as a function of magnetic field at two different frequencies and at two different delay times.

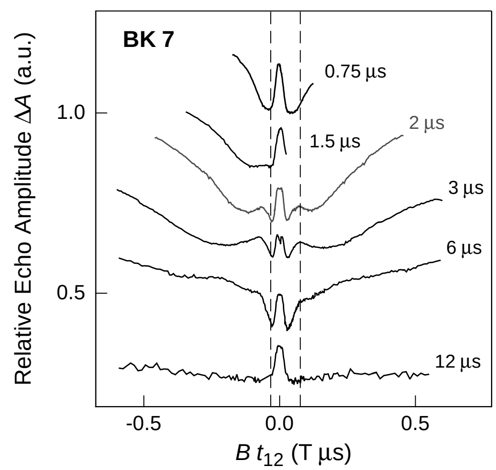

Fig. 2. Amplitude of two-pulse echoes generated in the borosilicat glass BK7 as a function of the product of magnetic field times the delay time t_{12}. The dashed lines mark the positions of typical features in the field dependence of the echo amplitude.

non-monotonic variation of the echo amplitude with magnetic field. The observation of the magnetic field effect in BK7 shows that magnetic impurities are not responsible for the occurrence of these phenomena, because this glass has a particularly small concentration of magnetic impurities.

Two remarkable conclusions can be drawn from the data shown in Fig. 1, namely that the variation with magnetic fields strongly depends on the delay time t_{12} and that a frequency dependence is almost completely absent. Note that the slight differences at higher fields ($B > 100\,\mathrm{mT}$) may be caused by experimental problems. The fact that the results are identical for different frequencies is very surprising, because it means that tunneling systems with very different energy splittings behave in exactly the same way. This cannot be understood in the models mentioned above [9,10], because in both theories the variation with magnetic field should depend on the absolut value of the tunnel splitting, if the effective magnetic moments of the systems are similar. The missing variation indicates, that the magnetic field effect observed in the two-pulse echo experiments is caused by a different mechanism.

The observation, that the magnetic field dependence is different for different delay times t_{12} demonstrates that the magnetic field influences the coherent motion of the tunneling systems during the free development of the phase of the tunneling states in the experiment. This becomes more obvious by plotting the echo amplitude as a function of the magnetic field times the delay time. A plot of this kind is shown in Fig. 2 for the data obtained in the measurements on BK7. All curves have been taken at 4.6 GHz except the one at $t_{12} = 2\,\mu\mathrm{s}$ which has been measured at 0.9 GHz. It is interesting that the central maximum of these curves has the same width for all measurements at different delay times and that the corresponding minima occur at the same position indicated by a vertical dashed line. This suggests a linear variation of the phase of the tunneling systems with the applied magnetic field. In addition, a small second maximum is observed, which also occurs for each curve at the same value of Bt_{12}. The values of Bt_{12} at which these distinct features are seen suggest that the involved magnetic moments are of the order of nuclear moments [8].

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