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Invited paper

μSR studies of the vortex lattice in high-T_c and other superconductors

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We review some of the assumptions made in the use of muon spin rotation in superconductors: i.e. that the muons are implanted at random positions in the flux lattice, remain static after implantation and do not appreciably affect the properties of the surrounding superconductor; also that the flux lines are straight and static, and that the observed muon rotation frequency spectrum reflects the microscopic distribution of field values. We shall show how evidence for and against the truth of these assumptions in particular cases may be obtained from the μSR results themselves or by comparison with other measurements, and how this in turn may lead to deeper understanding of flux line structure and motion in superconductors.

1. Introduction

When a sufficiently large field is applied to a superconductor for the magnetic flux to enter, the field either destroys superconductivity (“type-I” behaviour) or forms the “mixed state”, at an applied field denoted H_{c1} (“type-II” behaviour). In the latter case, the field enters in the form of lines of flux: associated with each line is one quantum of magnetic flux, $\Phi_0 = h/(2e)$, which is spread out over an area of dimension λ, the magnetic penetration depth of the superconductor. Circulating supercurrents flow in the same region. The “core” of each flux line is quasi-normal and occupies an area of dimension $\sim \xi$, the superconducting coherence length, which is less than λ. In the absence of complications, to be discussed below, these flux lines form a hexagonal lattice, with spacing that decreases with increasing field until finally the normal cores overlap and superconductivity is destroyed at a field H_{c2}. Some elements (e.g., Nb), many compounds, and all high-T_c materials are type-II, and in the mixed state in

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these materials, the magnetic field will be non-uniform, being highest at the flux line cores. Muons with their spins perpendicular to the field which are implanted at random positions within the superconductor will therefore experience a range of different fields and precess at different rates, leading to a damping of the muon-spin-rotation signal. This technique was first applied some years ago [1], but really flowered when high-T_c's came on the scene (see, e.g., [2]). For fields not too close to H_{c1} or H_{c2}, the width of the muon precession frequency distribution is proportional to Φ_0/λ^2 [3]; so, μSR can be used to establish both the value and temperature-dependence of the penetration depth (see, e.g., [2,4]). In fact, the early expression [3] relating λ to the rms width of the field distribution (and hence the damping) was not numerically correct [5,6], but there is a more severe problem than this in relating μSR results to λ. That is the question of the *shape* of the field distribution in the flux lattice, which has the theoretical form represented schematically in fig. 1. The maximum field of this distribution corresponds to muons arriving at the flux line cores and the minimum field to the region furthest from the cores; there is a (in principle infinite) peak at the value of field corresponding to a position half-way between two cores, where the field is saddle-shaped. This distribution is clearly highly asymmetrical and cannot simply be represented by a single number – the rms width, σ. In addition, the tail at high fields extends a very long way ($\sim 2H_{c1}$ above the average field), and if we lose the end of the tail (i.e. those few muons which arrive close to the cores) in experimental noise, then σ can be severely underestimated. For detailed work it is therefore essential to analyse data so as to give the complete *shape* of the field distributions, rather than just their observed width. This can most effectively be done by a maximum entropy technique [7,8], although FFT can also give lineshapes. It should be noted that under the conditions given above (fields not too close to H_{c1} or H_{c2}, which is possible if $\lambda \gg \xi$) the horizontal scale of *all* the features of the spectrum in fig. 1 is proportional

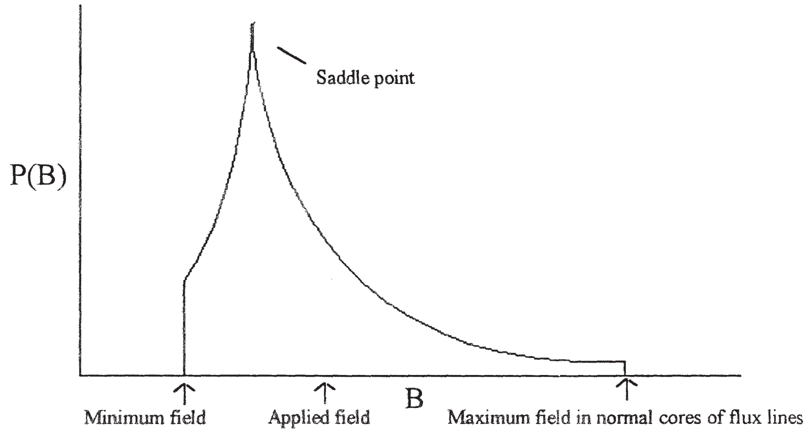

Fig. 1. Schematic representation of field distribution in the mixed state. The quantity plotted is the probability density $P(B)$ that a muon implanted at random in the flux lattice experiences a local field value B.

to Φ_0/λ^2. For instance, the high-field tail is approximately exponential, with a field scale $\sim \Phi_0/\lambda^2$; also the difference between the peak field and the mean field is proportional to the same quantity. Hence, several features, but particularly the peak position, may be used to establish the value of the penetration depth. It should also be noted that high-T_c materials are extremely anisotropic, so that supercurrents flow much more strongly within the conducting CuO_2 planes than perpendicular to them, so that the penetration depth λ is a function of supercurrent direction. ξ is similarly anisotropic and in a direction perpendicular to the planes is shorter than the spacing between planes, which can in some cases behave independently.

All of this discussion depends on the assumptions that in the mixed state there is a lattice of straight static flux lines at a uniform density, and that the muon acts as a static passive probe of the pre-existing flux line structure. If these assumptions break down, then the observations may not coincide with the simple picture presented in fig. 1, and the interpretation of the observed muon spin rotation spectra may have to be carried out with circumspection.

2. Are the muons static?

High-T_c materials seem almost ideally suited to investigation by μSR, since implanted muons become essentially chemically bound to an oxygen in the unit cell [9] and remain static over the temperature range below T_c. It is possible that a muon might modify the superconducting properties over a region ξ around itself; however, this will not appreciably alter the magnetic field at the muon due to surrounding static flux lines, since the magnetic field at any point is determined by supercurrents flowing in a region $\sim \lambda^3$ in size; this is many orders of magnitude larger than the region over which the superconducting properties might be affected (typically $\lambda \gtrsim 1400$ Å, $\xi \lesssim 20$ Å in the plane directions).

The implanted muons, although at a definite position within the unit cell, may be considered to arrive at *random* positions within the flux lattice, since both the spacing of flux lines (~ 1000 Å at a typical $B = 0.2$ T) and the value of λ are much larger than the unit cell size. Hence the muons should obtain an unbiased sample of the mixed state field distribution.

However, when muons are implanted in metals they can diffuse and this could alter the observed field distribution [10], leading at high diffusion rates to a “motional narrowing” or averaging of the field at the muon. We can report here on some recent measurements on the archetypal low-T_c superconductor Nb, which show that muon diffusion is not important in this case, confirming earlier results on the same material [11]. In fig. 2 is shown the temperature-dependence of the width of the field distribution, derived from the muon relaxation rate in the normal state of ultra pure (RRR $\sim$ 10 000) Nb. At high temperatures the relaxation is slow, because the muon is mobile, and the extra magnetic fields due to the Nb nuclei are motionally averaged to a small value. Usually in this temperature range, the rms width is higher

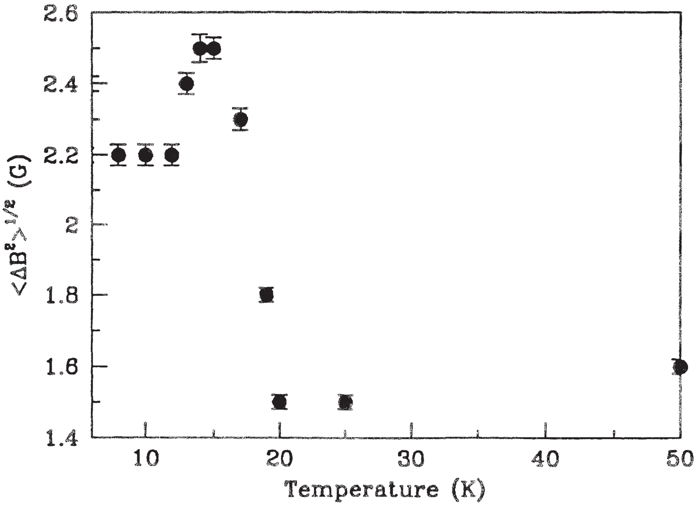

Fig. 2. Temperature-dependence of the rms linewidth of the μSR signal in the normal state of Nb. The field was 0.2 T (2 kG) applied along a (1 1 1) direction.

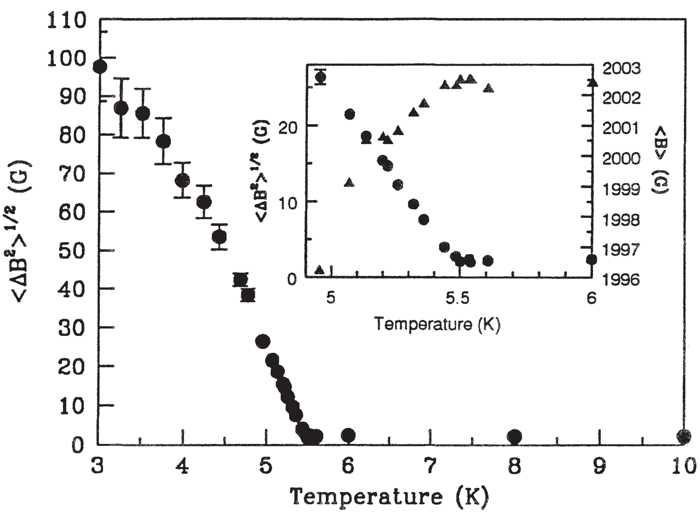

Fig. 3. The μSR linewidth in the mixed state of Nb versus temperature. The inset shows the rms width very close to $T_{c2}(H) = 5.5$ K at 0.2 T (circles), and the onset of superconductivity is indicated by the fall of the average internal field from the value applied in the normal state (triangles).

than we observe, because the muons diffuse to defects which have a larger range of local fields [12]. The small rms width we observe is confirmatory evidence for the excellent quality of our sample. However, as the temperature is lowered, the rms width rises slightly then remains constant at the value expected from the nuclei. Thus the muon diffusion has frozen out by $\sim$ 10 K and the muons are essentially at rest when the sample enters the mixed state, and will remain so, unless quantum diffusion takes over at still lower temperatures. Hence the μSR lineshape should accurately reflect theoretical expectations, unless the flux lines themselves are moving. In our experiments, we observed the expected lineshapes, just broadened by nuclear dipolar fields (compare [11]). In fig. 3 is plotted the temperature dependence of the linewidth. This shows all the way to T_{c2} ($H = 0.2$ T) a linear temperature-dependence of width as expected from Ginzburg–Landau theory. It therefore seems unlikely that the flux lattice in Nb melts well below H_{c2} as claimed on the basis of neutron scattering results [13].

3. Are the flux lines straight?

If flux lines are not straight, then their fields are smeared out and the field value distribution becomes narrowed. This is described in [14], where it is also pointed out that this kind of disorder should be contrasted with disorder in flux line *spacing*, which *increases* the width of the field distribution; (this effect has probably been observed in the less anisotropic material YBCO [15]). In the high-T_c superconductor BSCCO, the large anisotropy makes flux lines very “floppy” at short distances and flux lines can become “dislocated” into “pancake vortices”, each of which represents a section of a flux line passing through a CuO_2 plane. This has been clearly demonstrated by μSR [8] to occur in samples of BSCCO above a certain field $\sim$ 650 G and this has been confirmed by SANS [16]. It also seems to occur in organic superconductors which can be similarly anisotropic [17].

4. Are the flux lines static?

(*a*) *Evidence for flux lattice melting*

At low fields and low temperatures in BSCCO, the field distribution observed is close to that expected from flux lattice theory, plus a little broadening [8], but on heating at constant field the distribution loses all its high field tail at a certain temperature, and indeed the asymmetry of the lineshape becomes opposite; in addition the width drops markedly (fig. 4). All this occurs at a temperature close to that where the flux becomes macroscopically much more mobile – the “irreversibility line”, and these phenomena are clearly due to melting of the flux lattice. The narrowing of the distribution could be due to one or more of several causes: motion of straight flux lines, curvature of flux lines or even breaking-up of flux lines into pancakes. It is clear from neutron scattering data [16] that the flux lines are not straight in the melted state, since there is no detectable diffraction signal there: not even the broad ring that would be expected from a liquid of straight lines. No other evidence has been obtained that pancakes are connected into flux lines in the melted state in BSCCO, and

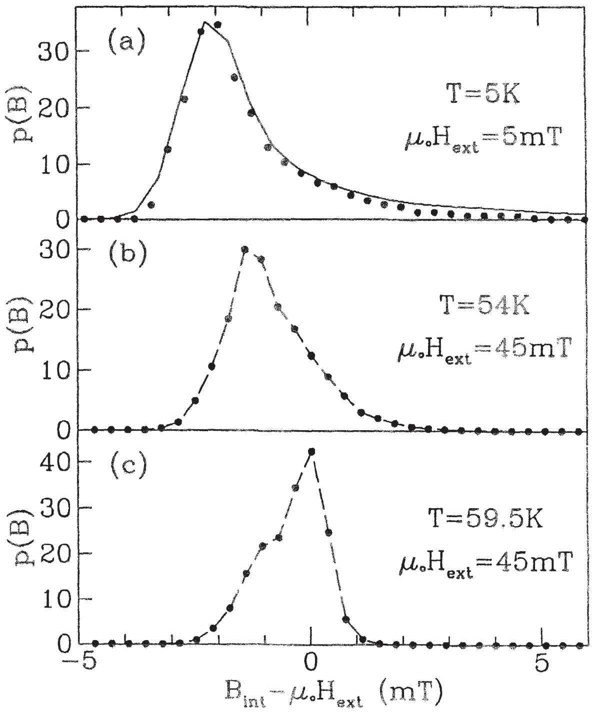

Fig. 4. μSR lineshapes (experimental data are points) in BSCCO after cooling in a field applied in the normal state perpendicular to the CuO_2 planes. (a) Low temperatures and low fields, showing the expected asymmetric lineshape. The solid line is a flux lattice simulation plus some broadening [8]. (b) Higher field and higher temperature, but the flux lattice is still solid. Dashed line is a guide to the eye. (c) Lineshape at a slightly higher temperature: the flux lattice has melted.

we believe that this state is most probably mobile pancakes, so that all three narrowing mechanisms apply.

(*b*) *Evidence for flux line vibrations*

Even when the flux lines are in a lattice, they cannot be completely static, since thermal vibrations of the lattice must be present at non-zero temperature. Such vibrations are believed to be sufficiently rapid that the muon will detect the thermally averaged fields of the flux lines. The main effect of this is that the field maxima at flux line cores become broadened to a width of $\sim \langle u^2 \rangle^{1/2}$ (thermal vibration amplitude) instead of ξ. The effect on the μSR lineshape is represented schematically in fig. 5. Recent observations in BSCCO [18] confirm this effect.

(*c*) *Evidence that pancake vortices can move*

Above the "crossover field" [8,16], flux lines in BSCCO are dislocated into pancake vortices. Any changes in the μSR lineshape with temperature in this region of field

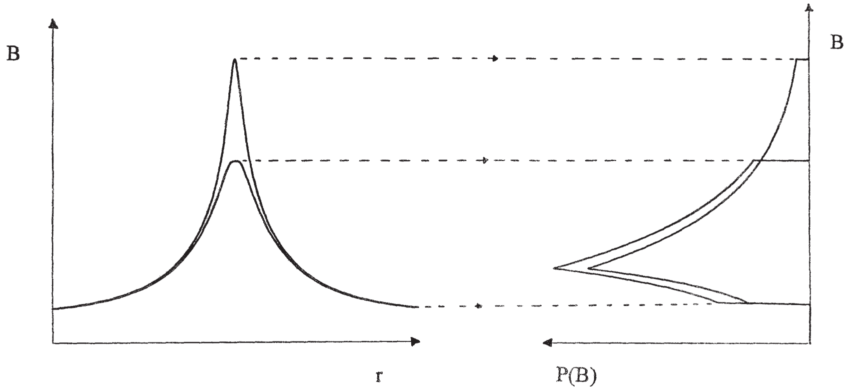

Fig. 5. “Smearing” of the core by flux line vibrations alters the field distribution.

may be a sign of pancake motion. The experimental evidence is as follows [8,19,20]: around 20 K, much lower than the irreversibility temperature, there is a change in lineshape, similar to that seen in melting at lower fields (but in a lineshape that is already narrower and more symmetrical, due to the dislocation into pancakes). If this effect is also due to melting, then it should be accompanied by a drop in the neutron scattering intensity also. In fact the precise opposite occurs [19]: there is a temperature and field region where the diffracted signal *increases* with increasing temperature and shows a sixfold lattice pattern just where the μSR signal appears liquid-like. A resolution of this apparent discrepancy is achieved if we assume that pancakes are *thermally depinned*, thus allowing the flux lattice to become more perfect and give an increased neutron diffraction signal; however, the thermal motion of the pancakes, if sufficiently rapid, can also give a motionally narrowed μSR lineshape. It appears that we have the first direct confirmation of an earlier claim [20] that μSR lineshapes in BSCCO at higher fields are strongly affected by pancake motion.

Some confirmatory evidence for our viewpoint is gained by considering another curious observation at high fields in BSCCO: that the average field seen by the muons increases as the temperature is lowered below $\sim$ 20 K [20–22]. It is clear that samples in this temperature region are magnetically irreversible, so no flux is moving in or out and the *actual* average field is remaining *constant* with temperature. However, if there is some correlation between muon and pancake positions [20], then the muons would give a signal corresponding to a higher field than the true average. At the fields of interest, the flux line spacing is $\sim$ 1000 Å, and it is hard to believe that the muon at the end of its track would travel this sort of distance to seek out a flux line or a flux line pinning site, as suggested in [20]. However, a flux line or pancake may move to the muon, once that is at rest, and may be aided in its motion by the transient heating introduced by the muon ionisation track. An attractive interaction is to be expected, since the positive charge of the muon will repel the holes responsible for superconductivity in the CuO_2 planes, creating a pointlike pinning site for a flux line or pancake.

Experimentally, this effect does not occur at low fields, where the pancakes are lined up into flux lines, so it appears only to be effective when the pancakes are pinned individually. Also, this effect disappears above $\sim$ 20 K; this is entirely consistent with our earlier deduction that pancakes are depinned from impurities in this temperature region, so that we would not expect the pancakes to be pinned by muons either.

5. Does the μSR spectrum reflect the microscopic field distribution?

We have just seen one way in which the μSR spectrum departs from the true microscopic field distribution; there is also another way that has recently become clear [23]. This explains the observation that in the melted state in BSCCO, the observed spectrum has a small tail to lower fields, whereas in the flux lattice state, the tail is at higher fields. The latter is easily understandable as being due to flux line cores, but it seems unlikely that there are “anticores” in the liquid. Instead, it appears that the liquid lineshape is dominated by *macroscopic* variations in field across the whole sample, which arise because of its non-ellipsoidal plate-like shape [24]. Such a variation is shown schematically in fig. 6; it is clear that if the whole of the sample is illuminated with the muon beam, a field distribution with a peak at high fields and a tail to low fields will result. This “sample geometry” effect is still present in the flux lattice region, but there it is swamped by the much larger microscopic field variations due to the flux lattice. However, if we wish to investigate the flux lattice state in more detail this sample geometry effect will have to be removed. Indeed, in the flux liquid and pancake regions, it may well be that the observed width of the μSR lineshape is dominated by the sample geometry effect, and the temperature dependence of the lineshape may merely represent the temperature dependence of the sample diamagnetism, since the magnitude of the macroscopic field variation is proportional to this.

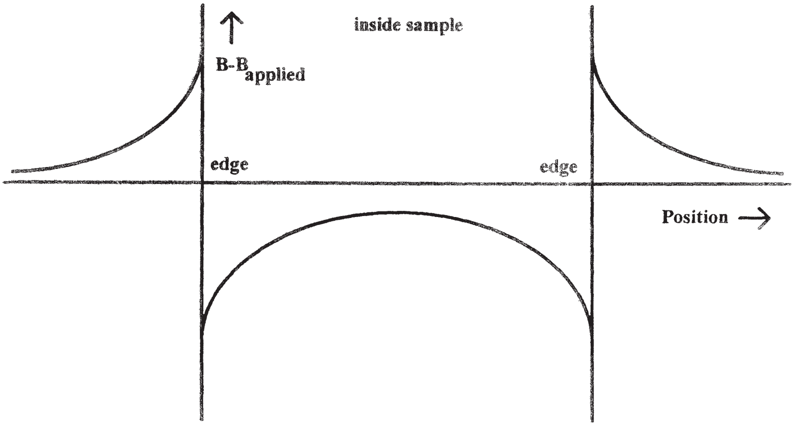

Fig. 6. Schematic representation of equilibrium induction versus position for a plate-shaped sample [24].

6. Summary and conclusions

We have presented evidence that the detailed interpretation of μSR lineshapes in the high-T_c superconductor BSCCO is not always completely straightforward. However, (sometimes with the aid of other measurements), we now have clear evidence of the melting of the flux lattice and its dislocation into pancakes at higher fields. Also, when in the flux lattice state, the flux lines do not move bodily on the timescale that muons are sensitive to, but they do vibrate. When pancakes become more independent at higher fields, they are pinned at lower temperatures but become mobile at higher temperatures. We may also expect that pancakes are mobile in the liquid state at higher temperatures.

We have concentrated on the results obtained in BSCCO so far; we may expect yet further developments, both in this material and also in the much less anisotropic YBCO investigated by other groups (see, e.g., [2,15]).

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