A novel high magnetic field (8 T) spectrometer for muon spin rotation ($\mu$SR) has been used to measure the temperature dependence of the in-plane magnetic penetration depth $\lambda_{ab}$ in YBa$_2$Cu$_3$O$_{6.95}$. At low $H$ and low $T$, $\lambda_{ab}$ exhibits the characteristic linear $T$-dependence associated with the energy gap of a $d_{x^2-y^2}$-wave superconductor. However, at higher fields $\lambda_{ab}$ is essentially temperature independent at low $T$. We discuss possible interpretations of this surprising new feature in the low-energy excitation spectrum.

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In a superconductor, the resistance to the flow of electrical current drops to an unmeasurably small value below a certain critical temperature $T_c$. This remarkable characteristic is due to the formation of pairs of electrons (or holes), called “Cooper pairs”, which link together and carry the charge through the sample with virtually no opposition. To break apart the pairs, an additional energy is needed to excite individual electrons above an energy gap which exists at the Fermi surface in the superconducting state. The nature of these elementary excitations, known as “quasiparticles” (QPs), is directly related to the size and symmetry of the energy gap. The gap itself reflects the symmetry of the pair wave function (or order parameter), knowledge of which is essential to understanding the physics of the underlying mechanism responsible for superconductivity.

A major breakthrough in the study of high-$T_c$ cuprate superconductors (HTSCs) came when it was realized that the symmetry of the energy gap was different from that in conventional low-$T_c$ materials. In particular, the energy gap was found to vanish along certain directions in momentum space. These so-called “nodes” serve as a conduit for extreme low-energy QP excitations. One of the key early experiments providing evidence for the existence of gap nodes was microwave measurements by Hardy et al. [1] of the in-plane penetration depth change $\Delta \lambda_{ab} = \lambda_{ab}(T) - \lambda_{ab}(1.35 \text{ K})$ in the Meissner state of high-purity YBa$_2$Cu$_3$O$_{6.95}$. In this phase, magnetic field is partially screened from the interior by “supercurrents” circulating around the sample perimeter. These supercurrents constitute the response of the superconductor to the applied field. The penetration depth $\lambda$ is the characteristic length scale over which the field decays in from the surface, and the quantity $\lambda^{-2}$ is proportional to the density of Cooper pairs, i.e. “superfluid density”, $n_s$. Because thermal energy can excite QPs, $\lambda^{-2}$ decreases with increasing $T$. In a conventional superconductor, this temperature dependence is typically weak at low $T$ because the isotropic energy gap exponentially cuts off the QP excitations as $T \to 0$ K. In Ref. [2], however, $\lambda_{ab}^{-2}$ was found to decrease sharply upon raising the temperature above 1.35 K—the lowest temperature reached in the experiment. This suggested that the minimum gap size was very small. Moreover, at low temperatures $\Delta \lambda_{ab}$ was observed to be proportional to $T$, which is characteristic of a superconducting order parameter which has $d_{x^2-y^2}$-wave symmetry (rather than $s$-wave symmetry as in conventional superconductors). Later the same behavior for $\lambda_{ab}^{-2}$ was observed in the vortex state of YBa$_2$Cu$_3$O$_{6.95}$, using the muon spin rotation ($\mu$SR) technique [2]. In the vortex state, magnetic field penetrates the sample in the form of quantized flux lines, called “vortices”, which usually arrange themselves into a periodic array. Screening currents circulate around the individual flux lines, so that here $\lambda_{ab}$ is associated with the decay of the field outside the vortex cores.

Recently, researchers have been wondering whether the story of the gap symmetry in the high-$T_c$ materials is complete. Some experiments performed at high magnetic fields in the vortex state show features which are seemingly inconsistent with a pure $d_{x^2-y^2}$-wave order parameter. For instance, scanning tunneling spectroscopy (STS) measurements in YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) suggest the existence of localized QP states in the vortex cores [3], which can only exist if there is an energy gap over the entire Fermi surface. Equally intriguing have been reports of an unusual plateau-like feature in the field dependence of the thermal conductivity $\kappa(H)$ in Bi$_2$Sr$_2$CaCu$_2$O$_8$ (BSCCO) [4,5], and underdoped YBa$_2$Cu$_3$O$_{6.83}$ [6]. A field-induced transition from a $d_{x^2-y^2}$-wave state to a fully gapped state, such as $d_{x^2-y^2} + id_{xy}$ or $d_{x^2-y^2} + is$, has been offered as a possible explanation for these results [6]. However, subsequent measurements of $\kappa(H)$ have established that the plateau is hysteretic [6] and is not observed in all samples [7]. These observations suggest that the vortex lattice (VL) and/or impurities are partially responsible for this feature.

Recent developments in spectrometer design at the TRI-University Meson Facility (TRIUMF) in Vancou-
ver, Canada have made it possible to extend the application of the \( \mu \)SR technique to magnetic fields as high as 8 T. This has allowed us to measure \( \lambda \) at fields where the anomalies in the STS and \( \kappa(H) \) measurements have been observed. In a \( \mu \)SR experiment the inhomogeneous magnetic field associated with the VL is sensitively measured by implanting muons into the sample, where their spins precess with a frequency which is directly proportional to the local field. The muon-spin precession signal which is obtained by detecting a muon’s positron-decay pattern, contains the precession frequencies from all the muon stopping sites. The line width of the corresponding field distribution is roughly proportional to \( \lambda^{-2} \).

Our measurements were performed on detwinned single crystals of YBa\(_2\)Cu\(_3\)O\(_{6.95}\) (\( T_c = 93.2 \) K), where a linear \( T \)-dependence has been previously observed at low \( H \). To generate a well ordered VL, the sample was cooled in the applied field. Neutron scattering measurements on a detwinned crystal of YBCO over the field range \( H = 0.2-4 \) T, show that at low \( T \) the vortices arrange themselves in a hexagonal lattice, distorted by \( \hat{a} \hat{b} \) anisotropy [1]. This is consistent with recent theoretical calculations which show that in a \( d_{x^2-y^2} \)-wave superconductor the VL is hexagonal at reduced fields \( H/H_{c2} < 0.15 \) [2].

An example of the measured muon spin precession signal is shown in Fig. 1(a). Although the time spectrum itself is not very revealing to the eye, a fast Fourier transform (FFT) can be performed, as in Fig. 1(b), to illustrate the distribution of precession frequencies (or local fields) in the sample. We stress that the frequency spectrum in Fig. 1(b) is only an approximation of the actual internal field distribution, because the finite time range and the “apodization” needed to eliminate “ringing” in the FFT artificially broadens the output spectrum [3]. We have previously shown that a sharp field distribution exists in high quality YBa\(_2\)Cu\(_3\)O\(_{6.95}\) crystals, with the basic features slightly smeared out by a small random displacement of the vortex positions and a small nuclear dipolar contribution [10]. Despite the shortcomings of the FFT procedure, the basic features of a hexagonal VL are recognizable in the observed asymmetric line shape—namely, the minimum field at the center of the triangle formed by three adjacent vortices is close to the cusp associated with the Van Hove singularity produced by the field at the center position between nearest-neighbor vortices. The observation of a high-field “tail”, related to the field in the vicinity of the vortex cores, is a signature of a well-ordered VL.

The inset of Fig. 1(b) shows the field dependence of the skewness parameter, \( \alpha = \langle (\Delta B)^3 \rangle^{1/3} / \langle (\Delta B)^2 \rangle^{1/2} \) [where \( \langle (\Delta B)^n \rangle = \langle (B - \langle B \rangle)^n \rangle \)], which characterizes the symmetry of the field distribution. The decrease in \( \alpha \) with increasing \( H \) is predicted to occur in both \( s \) and \( d_{x^2-y^2} \)-wave superconductors [12], and does not imply a change in VL geometry. The qualitative agreement between the behavior of \( \alpha(H) \) extrapolated to \( T = 0 \) K and at \( T = 50 \) K, suggests that the VL remains hexagonal over this temperature range.

The muon-spin precession signals were fit assuming an analytical Ginzburg-Landau (GL) model for the internal field profile associated with the VL [14]

\[
B(r) = B_0(1 - b^4) \sum_G \frac{e^{-G^2r} + K_1(u)}{\lambda_{ab}^2 G^2},
\]

where \( u^2 = 2\xi_{ab}^2G^2(1 + b^4)[1 - 2b(1 - b^2)] \), \( B_0 \) is the average internal field, \( G \) are the reciprocal lattice vectors, \( \xi_{ab} \) is the in-plane GL coherence length and \( K_1(u) \) is a modified Bessel function. The fitting procedure is described in detail elsewhere [14]. We have verified that the qualitative results described in this Letter are robust with respect to the theoretical model assumed for \( B(r) \). The solid curves in Fig. 1(a) are an example of a fit of the time spectrum to a theoretical complex muon polarization function \( P(t) = P_0(t) + P_1(t) \), assuming the field profile in Eq. (1) and a Gaussian distribution of fields for the small background signal barely visible in the FFT at 813.4 MHz.

Figure 2 shows the temperature dependence of \( \lambda_{ab}^{-2} \) at \( H = 0.5, 4 \) and 6 T. The solid curve in Fig. 2, which agrees very well with the \( H = 0.5 \) T data at low \( T \), represents the microwave measurements of \( \Delta \lambda_{ab} \) at zero DC field [1], converted to \( \lambda_{ab}^{-2} \) using the \( \mu \)SR value of \( \lambda_{ab} \) at \( T = 1.35 \) K. At the higher fields the linear \( T \)-dependence at low temperatures vanishes and the magnitude of \( \lambda_{ab}^{-2} \) is reduced. This occurs below \( T \approx 25 \) K and \( 35 \) K at \( H = 4 \) T and 6 T, respectively. While the nature of the QP excitations at low \( T \) is strongly influenced by the applied field, at intermediate temperatures (35 K < \( T < 60 \) K) the field has a negligible effect. At higher \( T \) the VL melts at a field-dependent temperature \( T_m(H) \), as shown by magnetization measurements on similar crystals [1]. In the melted region it is not straightforward to extract \( \lambda_{ab} \). The observed decrease in \( \lambda_{ab}^{-2} \) above \( T_m(H) \) arises from a loss of asymmetry in the measured field distribution. We now proceed to discuss the possible sources of the field-induced reduction of \( \lambda_{ab} \) at low \( T \).

The application of a magnetic field results in a shift of the QP energy levels due to the superflow [17]. In a \( d_{x^2-y^2} \)-wave superconductor the low-lying QP levels near the nodes are shifted below the Fermi surface, resulting in a QP current which flows in opposite direction to the superflow. This leads to a nonlinear relationship between the supercurrent density \( J_s \) and the superfluid velocity \( v_s \). The net result is a weakened supercurrent response, leading to an increased penetration of the field. In the Meissner state, Yip and Sauls [18] predicted that nonlinear effects in a \( d_{x^2-y^2} \)-wave superconductor give rise to a linear \( H \)-dependence for \( \lambda \) at \( T = 0 \) K. Although recent measurements of \( \lambda(H) \) [21] show evidence for some sort of nonlinear Meissner effect, they do not agree with the Yip and Sauls prediction, and do not show a saturation at low \( T \) as observed here.

According to Amin, Affleck and Franz [21], a more dominant contribution to the field dependence of \( \lambda_{ab} \)
measured by $\mu$SR, comes from the nonlocality of the supercurrent response in the vicinity of the gap nodes. In a clean $d_{x^2-y^2}$-wave superconductor the coherence length $\xi_0$, which is inversely proportional to the gap size, diverges at the nodes. Thus, near these regions of the Fermi surface, $\xi_0 > \lambda$, and $J_s$ at a point $r$ is obtained by averaging the field over a surrounding region of radius of $\xi_0$. For a non-uniform field, nonlocal effects weaken the supercurrent response. In Ref. [21], the effective $\lambda_{ab}(H)$ measured by $\mu$SR was calculated for the combination of nonlocal and nonlinear effects in a pure $d_{x^2-y^2}$-wave superconductor in the vortex state at $T = 0$ K. The result is that $\lambda_{ab}(H)$ is a nonlinear function of magnetic field, predominantly due to a modification of the field distribution by nonlocal effects. In Fig. 3 we show that our measurements of $\lambda_{ab}(H)$ agree extremely well with this prediction. Although no prediction for the temperature dependence of $\lambda_{ab}$ appears in Ref. [21], recent calculations show a continuous transition as a function of $T$ to the $T$-independent region [22]. We remark that nonlocal effects are not expected to play a role in the high-field experiments.

Another possible explanation for the saturation of $\lambda_{ab}^{-2}$ at low $T$ is that a field-induced transition to a fully gapped state has taken place which freezes out the QP excitations. This does not necessarily lead to a change in $\nu$ geometry—since as noted earlier, the $\nu$ is predicted to be hexagonal at low $H/H_{c2}$ irrespective of the pairing symmetry [12]. Furthermore, at low $T$ the vortices in YBCO are strongly pinned and probably reluctant to redistribute themselves. However, if a small imaginary component ($s$- or $d_{xy}$-wave) is induced by the field at low $T$, naively one would expect $\lambda_{ab}^{-2}(T)$ to saturate at a value equivalent to $\lambda_{ab}^{-2}(T \rightarrow 0)$ at $H = 0.5$ T, which is clearly not what we observe. Recently, Yasui and Kita [23] have shown by self-consistently solving the Bogoliubov-de-Gennes (BdG) equations, that the mixing of an $s$- or $d_{xy}$-wave component, if it exists, must gradually develop as a function of field in the vortex state. Although this is not inconsistent with our $\mu$SR measurements, the high-field plateau observed in the $\kappa(H)$ measurements [4] indicates a sharp field-induced transition of unknown origin. In Ref. [23] it is also shown that the double-peak structure observed near zero bias in the STS experiment of Maggio-Aprile et al. [3] can originate from low-energy QP hopping between the vortex cores of a pure $d_{x^2-y^2}$-wave superconductor—negating the need for the large $d_{xy}$ component suggested by Franz and Téšanović [4] in an earlier treatment of an isolated vortex using the BdG formalism. Thus, current theories can explain both the STS and $\mu$SR anomalies at high field in terms of a pure $d_{x^2-y^2}$-wave superconductor. We note that while the peak structure was not observed in STS measurements of the vortex cores in BSCCO by Renner et al. [2], a recent STS study by Davis et al. [24] shows evidence for QP core states in this material.

Finally, Fig. 4 shows the field dependence of the in-plane coherence length $\xi_{ab}$ from the fits to the $\mu$SR spectra, extrapolated to $T = 0$ K. Previously, we established that $\xi_{ab}$ is nearly proportional to the size of the vortex cores $r_0$, and that $r_0$ expands at low fields [20]. The high-field measurements clearly show that the core size saturates with $\xi_{ab} \approx 18.5$ Å when the density of vortices ($\sim H$) becomes large. The expansion of $r_0$ at low fields is qualitatively consistent with the predictions from a recent quasiclassical theoretical study of the vortex structure in pure $s$- and $d_{x^2-y^2}$-wave superconductors [12].

In summary, we observe a field-induced saturation in the temperature dependence of $\lambda_{ab}$ at low $T$ measured by $\mu$SR. The behavior of $\lambda_{ab}^{-2}(T)$ appears inconsistent with a transition to a mixed $d_{x^2-y^2} + id_{xy}$ ($d_{x^2-y^2} + is$) state. The measured field dependence of $\lambda_{ab}$ is in agreement with the theory of nonlocal and nonlinear effects in the vortex state of a pure $d_{x^2-y^2}$-wave superconductor.

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Figure 1. (a) The muon spin precession signal at $T = 20$ K and $H = 6.0$ T displayed in a reference frame rotating at about 3 MHz below the Larmor precession frequency of a free muon in the external field [Note: A is the maximum precession amplitude]. (b) The FFT of (a) using a Gaussian apodization with a 3 µs time constant. Inset: field dependence of the skewness parameter $\alpha$ extrapolated to $T=0$ K [solid circles] and at $T=50$ K [open circles].

Figure 2. Temperature dependence of $\lambda_{ab}^{-2}$ at $H=0.5$ T, 4 T and 6 T. The solid curve represents the zero-field microwave measurements of $\Delta \lambda_{ab}(T)$ in Ref. [1].

Figure 3. Magnetic field dependence of $\lambda_{ab}$ in YBa$_2$Cu$_3$O$_{6.95}$ extrapolated to $T = 0$ K [open circles] and the predicted behavior at $T=0$ K from Ref. [21] for the combination of nonlinear and nonlocal effects in the vortex state of a $d_{x^2-y^2}$-wave superconductor [solid diamonds].

Figure 4. Magnetic field dependence of $\xi_{ab}$ in YBa$_2$Cu$_3$O$_{6.95}$ extrapolated to $T = 0$ K.

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$YBa_2Cu_3O_{6.95}$

$\frac{1}{\lambda_{ab}^2} \text{ (}\mu\text{m}^{-2}\text{)}$

- $H=0.5\text{T}$ (solid circles)
- $H=4.0\text{T}$ (open circles)
- $H=6.0\text{T}$ (triangles)

$T$ (K)

$0$ $20$ $40$ $60$ $80$ $100$
$\lambda_{ab}(0,H)/\lambda_{ab}(0,0)$ versus $H (T)$

- **Open circles**: $\text{YBa}_2\text{Cu}_3\text{O}_{6.95}$
- **Filled diamonds**: nonlinear & nonlocal effects
$\xi_{ab}(T=0K)$ [Å]

$YBa_2Cu_3O_{6.95}$

$H (T)$