Magnetic Imaging of Pearl Vortices in Artificially Layered (Ba$_{0.9}$Nd$_{0.1}$CuO$_{2+x}$)$_m$/\(\text{CaCuO}_2\)_n Systems

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We have used scanning SQUID magnetometry to image vortices in ultrathin (Ba$_{0.9}$Nd$_{0.1}$CuO$_{2+x}$)$_m$/\(\text{CaCuO}_2\)_n high temperature superconductor samples, with as few as three superconducting CuO$_2$ planes. The Pearl lengths ($\Lambda = 2\lambda_L^2/d$, $\lambda_L$ theLondon penetration depth, $d$ the superconducting film thickness) in these samples, as determined by fits to the vortex images, agree with those by local susceptibility measurements, and can be as long as 1 mm. The in-plane penetration depths $\lambda_{\parallel}$ inferred from the Pearl lengths are longer than many bulk cuprates with comparable critical temperatures. We speculate on the causes of the long penetration depths, and on the possibility of exploiting the unique properties of these superconductors for basic experiments.

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Vortices play a central role in many aspects of superconductivity. Not only do the dynamics of vortices determine many of the transport properties of type II superconductors, especially the high critical temperature cuprates [1], but vortices are also of more general interest, since as topological defects they are of great relevance, for instance, to phase transitions [2,3]. The formation of topological defects in phase transitions has even stimulated some analogies between cosmology, gauge theories, and condensed matter physics [4,5]. Vortices in bulk type II superconductors were first predicted by Abrikosov in 1957 [6], and have since been imaged by many different experimental techniques [7]. Vortices in thin superconductors ($d \ll \lambda_L$, where $d$ is the superconducting film thickness and $\lambda_L$ the London penetration depth, respectively) were first described by Pearl [8] (hence “Pearl” vortices). Pearl vortices have several interesting attributes. The field strengths $h_z$ perpendicular to the films diverge as $1/r$ at distances $r \ll \Lambda$ in Pearl vortices, whereas in Abrikosov vortices the fields diverge as $\ln(r/\lambda_L)$ [9]. Since in the Pearl vortex much of the vortex energy is associated with the fields outside of the superconductor, the interaction potential $V_{int}(r)$ between Pearl vortices has a long range component $V_{int} \sim \Lambda/r$ for $r \gg \Lambda$ [8], unlike Abrikosov vortices, which have only short range interactions. The interaction between Pearl vortices $V_{int} \sim \ln(\Lambda/r)$ for $r \ll \Lambda$ leads to a Berezinski-Kosterlitz-Thouless (BKT) transition which is cut off due to screening on a scale $\Lambda$ [1]. The logarithmic interaction makes this system very similar to a Coulomb gas and ideal to study screening effects and renormalization in BKT transitions [10]. While superconducting vortices in films with thickness $d$ comparable to the London penetration depth $\lambda_L$ have been imaged using many techniques, to our knowledge the present work is the first to directly demonstrate experimentally the existence of Pearl vortices for $d \ll \Lambda$, and is also the first to use scanning susceptibility measurements to determine penetration depths in superconductors.

In the present work, two different types of (Ba$_{0.9}$Nd$_{0.1}$CuO$_{2+x}$)$_m$/\(\text{CaCuO}_2\)_n (CBCO) structures were grown: (a) the ultrathin (Ba$_{0.9}$Nd$_{0.1}$CuO$_{2+x}$)$_m$/\(\text{CaCuO}_2\)_n plane and (b) the relatively thicker (Ba$_{0.9}$Nd$_{0.1}$CuO$_{2+x}$)$_m$/\(\text{CaCuO}_2\)_n superlattices with $S \geq 15$ of the (Ba$_{0.9}$Nd$_{0.1}$CuO$_{2+x}$)$_m$/\(\text{CaCuO}_2\)_n superlattices composed of $m$ Ba-based and $n$ Ca-based unit cells. All the samples were grown on (001) SrTiO$_3$ substrates, with nominally zero miscut angle, by pulsed laser deposition (PLD), using a focused KrF excimer pulsed laser source ($\lambda = 248$ nm) with energy areal density on the target surface of 7 J/cm$^2$ in a spot size of 2 mm$^2$. Two sintered powder targets, with a nominal composition of (Ba$_{0.9}$Nd$_{0.1}$)CuO$_2$ and CaCuO$_2$, mounted on a multitarget system, were used. The substitution of 10% of the Ba atoms with trivalent Nd cations, even if not strictly necessary for superconductivity [11,12], helped us to find the right growth conditions by slightly decreasing the uncompensation of the electrical charge in the CR block. The growth temperature was about 640 °C and the molecular oxygen pressure was $= 1$ mbar. At the end of the deposition procedure, an amorphous protecting layer of electrically insulating CaCuO$_2$ was deposited on top of the film at a temperature lower than 100 °C.

The SQUID microscope measurements were made at 4.2 K with the sample cooled and imaged in fields of a few mG, sufficient to trap several vortices in a
200 \mu m \times 200 \mu m scan area. Two types of SQUID sensors were used: (1) magnetometers \cite{13} with either square pickup loops 7.5 \mu m on a side, or octagonal pickup loops 4 \mu m in diameter; and (2) SQUID susceptometers \cite{14} with a single turn field coil 20 \mu m in diameter, with a square pickup loop 8 \mu m across [see Fig. 2(a)].

We have performed scanning SQUID microscopy (SSM) on various 5/2/5 monolayers, 5/2/5/2/5 bilayers and CBCO $m \times n$ samples, and as a function of the number of the CuO$_2$ planes. In all systems we have clearly observed Pearl vortices. This provides evidence of superconductivity complementary to traditional transport measurements \cite{15} for the thinnest films. We show in Fig. 1 SSM images of vortices trapped in two typical samples. The thin-film limit for the two-dimensional Fourier transform of the $z$ component of the field from an isolated vortex trapped in a thin film is given by \cite{8,16}:

$$h_z(k, z) = \frac{\phi_0 e^{-kz}}{\Gamma + k\Lambda}, \quad (1)$$

where $z$ is the height above the film, $k = \sqrt{k_x^2 + k_y^2}$, $\Lambda = 2\lambda_{ab}^2/d$ is the Pearl penetration length, $\lambda_{ab}$ is the in-plane penetration depth, $d$ is the film thickness, and $\phi_0 = hc/2e$. We fit the data in Fig. 1 by inverting Eq. (1) to find $h(x, y, z)$, integrating the result over the known pickup loop geometry, and using $\Lambda$ as the fitting parameter. The height $z$ was determined by fitting images of vortices in Nb with the same SQUID magnetometer, assuming an isotropic low temperature Nb penetration depth of $\Lambda = 0.05 \mu m$ \cite{17}. We note that although the peak SQUID flux $\phi_z$ depends strongly on $\Lambda$, the full-width at half-maximum of the vortex images is relatively independent of $\Lambda$ for such thin films. For comparison, Abrikosov vortices typically couple about $0.5\phi_0$ of flux into the SQUID sensor in this geometry, and are resolution limited.

The results for the Pearl lengths $\Lambda$ from such fits to images of vortices for a number of superlattice samples are summarized in Table I. The results for the Pearl lengths

![FIG. 1. SQUID microscope image and cross-sectional data (along the positions indicated by the dashed lines in (a),(c)) of vortices trapped in two CBCO samples. The SQUID pickup loops were a square 7.5 \mu m on a side (a),(b) and an octagon 4 \mu m on a side (c),(d). The open symbols in (b),(d) are the cross-sectional data; the solid lines in (b),(d) are fits to Eq. (1). Scaled schematics of the pickup loops used appear in (a),(c).](image)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Type</th>
<th>Cells</th>
<th>$d(\AA)$</th>
<th>$d_{IL}(\AA)$</th>
<th>$T_c(K)$</th>
<th>$\Lambda (\mu m)$</th>
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<td>50</td>
<td>6.4</td>
<td>30</td>
<td>128</td>
</tr>
<tr>
<td>1151</td>
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<td>1</td>
<td>50</td>
<td>6.4</td>
<td>35</td>
<td>205</td>
</tr>
<tr>
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<td>1</td>
<td>79</td>
<td>12.8</td>
<td>50</td>
<td>292</td>
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<tr>
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<td>5/2/5/2/5</td>
<td>1</td>
<td>79</td>
<td>12.8</td>
<td>50</td>
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<td>76.8</td>
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<td>25</td>
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<td>304</td>
<td>123</td>
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<tr>
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<td>426</td>
<td>179.2</td>
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<td>426</td>
<td>96</td>
<td>60</td>
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</table>

TABLE I. Pearl lengths $\Lambda$ of various CBCO samples $T_c$ is measured by standard four-probe techniques and refers to zero resistance. We estimate uncertainties in $\Lambda$ of $\pm 20\%$ and of $T_c$ of $\pm 0.25$ K.
of about 5.0 μm, as determined by fits of similar data using a Nb sample, assuming a Nb penetration depth of 0.05 μm. In principle, the mutual inductance should saturate when the SQUID substrate contacts the sample. Experimentally there continues to be some change, presumably because the tilt angle between the substrate and the sample decreases.

The 2D Fourier transform of the z component of the field in the pickup loop, with a current I in a circular ring of radius R oriented parallel to, and a height z above a sample, is given by [19]

\[ h_z(k) = -\frac{4\pi^2 IR}{c} J_1(kR) \left( 1 - e^{-2kz} \right) / \left( 1 + k\Lambda \right) \]  

(2)

where \( J_1(kR) \) is a Bessel function of the first kind. The solid line in Fig. 2(b) is obtained by numerically integrating the 2D Fourier transform of Eq. (2) over the area of the pickup loop, for various values of z, and fit to the data by varying \( \Lambda \). Figure 2(c) compares the values obtained for the Pearl lengths for a number of the CBCO samples using magnetometry and susceptibility methods. The two methods agree within experimental error over the range of Pearl lengths present [20].

As expected, the Pearl lengths are longest for the thinnest CBCO films. Figure 3 shows that the CBCO penetration depths \( \lambda_{ab,h} = \sqrt{d\Lambda/2} \) obtained assuming a homogeneous film (solid circles) are longer than for a number of hole-doped cuprates with comparable critical temperatures [21–23]. For example, optimally doped YBa\(_2\)Cu\(_{3-o}\)O\(_{7-\delta}\) (Y-123), with a \( T_c \) of 92 K, has \( \lambda_{ab,h} \approx 0.15 \) μm [24]. The highest \( T_c \), CBCO sample (sample 1985, \( T_c = 78 \) K) has \( \lambda_{ab,h} = 0.48 \) μm. Our samples span a wide range of Pearl lengths and sheet resistances per square. Detailed measurements of the latter are given elsewhere [11,15]. The 2 × 2 superlattices have resistance per square values a factor of 10 lower than the metal-insulator limit in the 2 × n superlattice series [11]. Since the mean free path in the high resistivity(but metallic, \( n \approx 11 \) or 5/2/5/2/5) films can be no shorter than the width of a CuO\(_2\) unit cell (≈ 4 Å), and since the normal state carrier sheet densities and effective masses should be similar within this series, this implies that the mean free paths in the 2 × 2 superlattices must be at least a few times larger than the in-plane coherence length (\( \xi \approx 20 \) Å), and that the Pippard correction for the effect of a finite mean free path \( \lambda \), \( \lambda_{eff} = \lambda_{l}(1 + \xi/\Lambda)^{-1/2} \), cannot be large. The London approximation (\( \lambda_{LT}^2 = m^*e^2/4\pi\kappa_n e^2 \)), [25], where \( m^* \) is the effective mass of the charge carriers) may therefore be reasonable to evaluate the superfluid density for this type of structure. If we use the standard London expression and a reasonable value of \( m^* = 5m_e \) [26], we obtain \( n_s = 6.29 \times 10^{21} \) cm\(^{-3}\) for optimally doped Y-123, as compared with \( n_s = 6.28 \times 10^{20} \) cm\(^{-3}\) for the highest \( T_c \), CBCO sample (1985). The corresponding areal superfluid densities per plane \( n_{p} = n_s d/N_p \) are 3.67 × 10\(^{14}\) cm\(^{-2}\) for optimally doped Y-123 and 3.2 × 10\(^{13}\) cm\(^{-2}\) for CBCO sample 1985 (\( N_p \) is the number of superconducting CuO\(_2\) planes). The superfluid...
densities for the CBCO samples are about a factor of 10 lower than for Y-123, although they have comparable $T_c$’s.

It has been proposed that the superfluid screening in films could be suppressed by proximity to the metal-insulator transition [27] or quantum fluctuations [28]. However the $2 \times 2$ superlattices have normal state resistances 10 times smaller than the metal-insulator critical resistance of $\approx 26 \, \mu\Omega$ [11]. It appears that the penetration depths in these films are significantly larger than bulk cuprates with comparable $T_c$’s. This may mean that these compounds are more efficient at producing high $T_c$’s from a given superfluid density [29].

A clue to how this could come about comes from considering the layered structure of these films. If instead of assuming that the superfluid densities are homogeneously distributed, we assume instead that all of the superfluid density is localized in the IL layers, then $\lambda_{ab,IL} = \sqrt{d_{IL} \Lambda}/2$. In this case the calculated penetration depths (the crosses in Fig. 3) become comparable to the longest penetration depths reported for some cuprates: Although the average superfluid density in these films is low, the density in the IL layers might be higher, possibly promoting superconductivity at high temperatures.

We also note that the areal superfluid densities are about $2 \times 10^{14} \, \text{cm}^{-2}$ for the $5/2/5$ structures, making them ideal candidates for field effect experiments. The height of the surface barrier $E_s$ to formation of vortices is one of the crucial parameters to observe vortex quantum tunneling (VQT) [30]. $E_s$ is proportional to $\phi_0^2/(8\pi^2\Lambda)$ and therefore inversely proportional to $\Lambda$: the larger the Pearl length, the lower the barrier height.

In conclusion, we have investigated vortex matter in ultrathin $[\text{Ba}_{0.9}\text{Nd}_{0.1}\text{CuO}_{2+x}]_{m}/[\text{CaCuO}_2]_n$ systems using scanning SQUID magnetometry and susceptometry. We have given the first experimental evidence for Pearl vortices in the regime $d \ll \lambda$. This can be considered the closest attempt yet to investigate vortices in two-dimensional systems (vortices of zero length). This experiment proves that extreme regimes (ultrathin films) are experimentally accessible through SSM and opens up several prospects of broad interest, especially if we consider that these topological defects may have analogies in other fields of physics. These measurements identify systems with very long penetration depths and relatively high $T_c$. This represents a further step to experimentally isolate the properties important for superconductivity in high-$T_c$ compounds. Finally, these systems potentially represent ideal systems to test novel theories and concepts for devices (VQT and field effect experiments).

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