Stress Dependence of Exciton Relaxation Processes in Cu$_2$O

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A comprehensive study of the exciton relaxation processes in Cu$_2$O has led to some surprises. We find that the ortho-para conversion rate becomes slower at high stress, and that the Auger nonradiative recombination rate increases with stress, with apparently no Auger recombination at zero stress. These results have important consequences for the pursuit of Bose-Einstein condensation of excitons in a harmonic potential.
I. INTRODUCTION

Cu$_2$O has long been studied as an textbook example of exciton physics. In the past decade, it has attracted attention as a system in which Bose condensation of excitons may occur [1–4]. The interpretation of these experiments has been the subject of debate, however, because many of the basic relaxation processes of the excitons in Cu$_2$O have remained unknown.

Two processes in particular have remained controversial. The first is the Auger nonradiative recombination process. Some authors have argued that Auger recombination of the excitons effectively prevents Bose condensation [5], while others have argued that this process is unimportant [6]. The theoretical estimates [7] of this effect are orders of magnitude different from experimental numbers [8,9].

The second process under debate is the conversion mechanism from orthoexcitons to paraexcitons. Several authors have argued for a collisional conversion mechanism [8], while others have argued for a phonon emission mechanism [5]. Various phonon emission mechanisms have been proposed [10,11]; previous work indicated a single acoustic phonon emission process [11], but questions have remained.

In this work we present the results of a series of experiments studying these effects. We have confined the excitons in a harmonic potential to keep their volume nearly constant, and have varied the stress, temperature, and exciton density, while observing both the orthoexciton and paraexciton luminescence as a function of time. This has allowed us to make substantial progress in understanding these mechanisms.

II. EXPERIMENT

For these experiments, we created a harmonic potential trap for the excitons using inhomogeneous stress using the method discussed in a previous publication [9]. We created orthoexcitons with kinetic energy approximately 1 meV by tuning the laser light to photon
energy 15 meV above the orthoexciton ground state in the trap. A strong phonon-assisted absorption process exists in Cu$_2$O which leads to the emission of a 14-meV optical phonon and the creation of an orthoexciton. Because the energy of the excitonic absorption band in the trap is below that of the unstressed bulk of the crystal, when the laser photon energy is tuned to this energy, the laser photons pass through the bulk of the crystal and are only absorbed in the trap.

The laser pulse, generated by a modelocked, cavity-dumped picosecond dye laser, is 2-5 picoseconds in duration and has negligible uncertainty broadening, much less than 1 meV. The cavity dumper allows us to have a long period between pulses (typically 260 ns) so that almost no excitons remain from one excitation pulse to the next. We observe the luminescence from the paraexcitons and orthoexcitons in the trap as a function of time after the laser pulse. Orthoexcitons decay either via a single-photon direct emission process or a phonon-assisted recombination, while paraexcitons decay primarily only via a single-photon direct recombination process, which is forbidden by symmetry at zero stress but which becomes allowed at high stress. The orthoexciton phonon-assisted luminescence intensity is directly proportional to the total orthoexciton population at all times; the paraexciton direct-recombination luminescence intensity is proportional to the paraexciton population and also, in principle, depends on the temperature, since only low-momentum paraexcitons can participate in the direct recombination process. Our fits indicate that this temperature dependence is very weak, however, and therefore we simply assume that the paraexciton luminescence intensity is directly proportional to the paraexciton density in fitting the data.

We can measure the energy spectrum of the exciton luminescence with 40 ps time resolution using time-correlated single photon counting. It is important to use the entire time-resolved spectrum of the luminescence for these measurements, because incorrect conclusions can be deduced by looking only at luminescence from one wavelength. We can also measure the spatial profile of the luminescence with the same time resolution using the scanner method reported elsewhere.

The stresses are calibrated using the luminescence line positions of the orthoexcitons and
paraexcitons, based on the reported shifts of the lines with stress [14,15].

The crystal temperature was held at 2 K in immersion in liquid helium for most of the experiments; we also performed experiments at higher temperature in helium vapor. The excitons have higher than the lattice temperature for a few nanoseconds after the laser pulse, since they are created with 1 meV excess energy, and the orthoexciton generation process also creates optical phonons which may cause a local heating.

III. STRESS DEPENDENCE OF THE ORTHO-PARA CONVERSION RATE

The first surprise from these experiments is that the ortho-para conversion rate becomes slower with increasing stress. Fig. 1 shows orthoexciton luminescence decay data for several stresses at very low excitation density. The decay is single exponential in each case. Because there are also density-dependent processes in Cu$_2$O, as discussed in the Section [V], we used very low laser power (1 mW) for these measurements. We verified that the time evolution did not depend on laser power by recording the orthoexciton lifetime for two powers different by a factor of ten.

Fig. 2 shows a summary of the orthoexciton decay time at low density as a function of the ortho-para splitting energy, which in turn depends on the stress. In general, the decay of the orthoexcitons at low density comes not only from ortho-para conversion but also from radiative recombination of orthoexcitons and recombination at impurities. As shown in previous measurements at high temperature [13] (verified by this study, as discussed in Section [V]), the orthoexciton radiative recombination lifetime is greater than 300 ns, so that radiative recombination of orthoexcitons gives negligible contribution to the orthoexciton decay.

We can understand this effect in terms of emission of a single acoustic phonon, as illustrated in the inset of Fig. 2. This mechanism was proposed in a previous publication [11] to explain the temperature dependence of the luminescence lines in Cu$_2$O. That publication successfully explained some results, but contained an error in the $k$-dependence. Correcting
that error allows us to fit the data with the curve shown in Fig. 2.

The dependence on $\Delta$ can be understood as arising from a $k$-dependence of the acoustic phonon emission process. As the ortho-para splitting is decreased, the momentum of the phonon emitted is decreased, as illustrated in the inset of Fig. 2. Since at low temperature the orthoexcitons have nearly zero $k$-vector, and since the acoustic phonon emission is essentially a horizontal process, the $k$-vector of the phonon is essentially equal to the momentum of the final para state. Since the paraexciton kinetic energy is proportional to $k^2$, the magnitude of $k$ is proportional to $\Delta^{1/2}$.

In Ref. [11], the $k \cdot p$ matrix element was given as proportional to $k_o$, the orthoexciton momentum, but this is an incorrect estimation of the matrix element. In $k \cdot p$ theory [17], the orthoexciton and paraexciton states can be written as

\[
|o(k_o)\rangle = |o(0)\rangle + i|p|o(0)\rangle
\]

\[
|p(k_p)\rangle = |p(0)\rangle + i|p|p(0)\rangle
\]

where $k_o$ and $k_p$ are the ortho and para momenta, respectively, and $|i\rangle$ is some intermediate state. The phonon scattering rate is therefore proportional to

\[
|\langle o(k_o)|M_q|p(k_p)\rangle|^2 = |\langle o(0)|M_q|i\rangle k_p \cdot \langle i|p|p(0)\rangle + \langle i|M_q|p(0)\rangle\langle o(0)|p|i\rangle \cdot k_o|^2
\]  

(1)

where $M_q$ is the exciton-phonon deformation potential matrix element for a phonon with momentum $q$. At low temperature, the orthoexciton momentum $k_o$ is negligible compared to the paraexciton momentum. Therefore we can drop the second term above, and assume that the rate is proportional to $k_p^2$ and set $q = k_p$. The deformation potential matrix element for phonon emission is given by [18]

\[
|M_q|^2 = \frac{\hbar \Xi^2 q}{2 \rho v V} (1 + n_q)
\]  

(2)

where $\Xi$ is a deformation potential, $\rho$ is the crystal mass density, $v$ is the acoustic phonon velocity, and $n_q$ is the number of phonons in state $q$. Since this process involves spin conversion, the deformation potential $\Xi$ used here is not necessarily the same as the deformation
potential for acoustic phonon relaxation without spin flip, determined in previous experiments \cite{19}. For an orthoexciton with $k_o \simeq 0$, the phonon emission rate is therefore proportional to

$$
\Gamma \propto \int d^3k_p \left[ k_p^2 \Xi^2 \delta(\Delta - \hbar^2 k_p^2/2m - \hbar \nu k_p) \left( 1 + \frac{1}{e^{\hbar \nu k_p/k_BT} - 1} \right) \right. $$

$$
+ \left. k_p^2 \Xi^2 \delta(\Delta - \hbar^2 k_p^2/2m + \hbar \nu k_p) \left( 1 + \frac{1}{e^{\hbar \nu k_p/k_BT} - 1} \right) \right],
$$

(3)

where we have included both the phonon emission and absorption terms. The phonon absorption term is similar. Using the $\delta$-function to remove the integration over $k_p$ yields

$$
\Gamma \propto \frac{k_p^5}{\hbar k_p/m + v} \left( 1 + \frac{1}{e^{\hbar \nu k_p/k_BT} - 1} \right) + \frac{k'_p^5}{\hbar k'_p/m - v} \left( 1 + \frac{1}{e^{\hbar \nu k'_p/k_BT} - 1} \right),
$$

(4)

where $k_p = (\sqrt{2\Delta m} - vm)/\hbar$ and $k'_p = (\sqrt{2\Delta m} + vm)/\hbar$. This formula gives the curve shown in Fig. 2, which is fit to the data by an overall multiplier.

Ref. \cite{11} reported essentially no stress dependence of the ortho-para conversion rate, but the data were over a much narrower range of stress, and the conversion rate was deduced based on the total intensities, which is a much more indirect method than that used here.

The phonon-assisted conversion rate (3) also implies that the ortho-para conversion rate depends on temperature. In the limit of low temperature, phonon absorption is negligible, and $n_q \simeq k_BT/\nu K_p$, which implies $\Gamma \propto (1 + aT)$. A weak temperature dependence consistent with this prediction has been reported in Ref. \cite{20} for the case of zero stress; we also have measured a weak temperature dependence consistent with this formula; the ortho-para conversion rate increases by approximately a factor of two when the temperature is raised from 2 K to 10 K. This is one of the strong arguments against an early proposal \cite{10} that an optical phonon is involved in the conversion process; if an optical phonon was emitted, the rate would increase much more rapidly with temperature.

**IV. STRESS DEPENDENCE OF THE AUGER CONSTANT**

It has long been proposed that an Auger process exists in Cu$_2$O by which two excitons collide, resulting in the annihilation of one and ionization of the other. Strong evidence of this process was provided by strain well experiments by Trauernicht et al. \cite{7}.
Ref. [9] reported the measurement of an Auger rate constant for excitons in a strain well in Cu$_2$O. That work reported data for only one, moderate stress (2.5 kbar). Furthermore, at early times after the laser pulse, the paraexciton data were obscured by hot orthoexciton luminescence. In the present work, we report data for several stresses, and we have clearly resolved the paraexciton luminescence by recording the full luminescence spectrum at all times after the laser pulse for all excitation densities.

Surprisingly, we find that the Auger rate depends on the stress. This is consistent with the prediction of Baym and Kavoulakis [7] that the Auger rate should be negligible at zero stress and increase with stress. We see no evidence of a two-body spin-flip mechanism [6], however.

Figs. 3 and 4 show the integrated ortho and paraexciton luminescence intensities for two different laser powers, in a strain well with 3.5 kbar stress, at $T = 2$ K. The evolution is clearly different at high exciton density. The dark lines are a fit to the coupled rate equations

$$\frac{dn_o}{dt} = -\frac{n_o}{\tau_{o-p}} - A_o n_o^2 + \frac{3}{8} (A_o n_o^2 + A_p n_p^2) - \frac{n_o}{\tau_o}$$

$$\frac{dn_p}{dt} = \frac{n_o}{\tau_{o-p}} - A_p n_p^2 + \frac{1}{8} (A_o n_o^2 + A_p n_p^2) - \frac{n_p}{\tau_p}.$$

The terms with $A_o$ and $A_p$ are the ortho and para Auger rates, respectively. One half of these terms are added back to the ortho and para populations due to ionized excitons reforming; it is assumed that $3/4$ of these return as orthoexcitons and $1/4$ as paraexcitons since the spin is assumed to be randomized upon ionization. In general, we could also include a cross term for collisions between orthoexcitons and paraexcitons, but we have been unable to fit the data with such a term.

The ortho-para conversion time $\tau_{o-p}$ depends on temperature, as indicated by Eq. (3); as shown in Ref. [10] and confirmed by this study, the conversion rate is faster at higher temperature. Since the temperature falls in time, the ortho-para conversion rate is assumed to vary in time according to

$$\frac{1}{\tau_{o-p}(t)} = C \exp(-t/\tau_T) + \frac{1}{\tau_{o-p}},$$

(6)
where $\tau_T$ is on the order of 10 ns and $C$ is a unitless constant which gives the fractional increase of the rate. These are not free parameters, because measurements of the spectral width of the exciton luminescence as a function of time constrain the temperature evolution.

Fig. 5 shows the full width at half maximum (FWHM) of the orthoexciton phonon-assisted luminescence for the two cases of Figs. 3 and 4. The dark lines are the FWHM implied by the fits of Figs. 3 and 4, because the FWHM of the phonon-assisted line in a three-dimensional harmonic potential is equal to $3.4k_BT$. At late times, both lines have FWHM of 0.75 meV, which corresponds to the expected FWHM of the phonon-assisted line at $T = 2$ K convolved with the spectral resolution of 0.5 meV. (Our spectral linewidth measurements also confirm the result reported by Trauernicht et al. [21] that the paraexciton luminescence in the strain well always has narrower spectral width than the orthoexciton luminescence at the same temperature, due to the peculiarities of the stress-allowed direct recombination process.)

The lifetimes $\tau_o$ and $\tau_p$ represent the total recombination rate due to radiative recombination and recombination at impurities. As shown earlier, and confirmed here, the radiative recombination rate for orthoexcitons and paraexcitons in Cu$_2$O is extremely low and essentially negligible. We find that in this sample the paraexcitons have a total recombination rate on the order of 20 ns at low temperature, however. This is presumably due to recombination at impurities. These fits indicate that the conversion to paraexcitons is the dominant decay channel for orthoexcitons, however, which means that their lifetime for recombination at impurities must be greater than 100 ns. If the orthoexcitons decayed by other channels than conversion to paraexcitons, we would not see as many paraexcitons at early times.

The paraexciton luminescence efficiency is different from that of the orthoexcitons; therefore another parameter is introduced in these fits which is an overall multiplier for the paraexciton luminescence. This overall multiplier depends on the stress since the paraexciton radiative recombination rate increases as the square of the shear stress. As mentioned above, in principle this multiplier also depends on temperature and therefore also changes in time, but we do not see evidence for this effect. One reason may be that the polariton
region of the paraexcitons covers a spectral region comparable to $k_B T$ at high stress.

Although these fits have several parameters ($\tau_{o-p}, \tau_p, A_o, A_p$, and the overall multiplier for the para intensity, $R_p$), the fits are highly constrained by the large amount of data. The same set of parameters must fit both the ortho and para data at all times and at all densities, with the exception that we allow the constant $C$ used in the time dependence of $\tau_{o-p}$ to become higher at high density, consistent with the increase of temperature which occurs when the Auger process is important.

The same set of equations have been used to fit the ortho and para data at other stresses. Figs. 6 and 7 show the fits for 2.5 kbar. As seen in these figures, the fits to Equations (5) are very good. Fig. 8 shows the fit for high exciton density at 1.5 kbar. At this stress the orthoexciton luminescence partially obscures the paraexciton data at early times, so that we cannot fit the paraexciton data at those times. Surprisingly, however, for the 1.5 kbar orthoexciton data there is essentially no Auger effect, implying that the Auger rate depends on the stress. Fig. 9 shows the orthoexciton data at 1.5 kbar at three laser powers, 100 mW, 10 mW, and 1 mW, multiplied by overall factors of 1, 10, and 100, respectively. As seen in this figure, all the curves decay in the same way; there is no evidence for any density dependence. The nonexponential nature of the decay can be explained as due to the temperature dependence of the ortho-para conversion process. Data taken at 2 kbar show similar behavior, with only slight dependence of the decay on the exciton density. We can be certain that the exciton densities are comparable at the different stresses, because the number of photon counts from the phonon-assisted orthoexciton luminescence immediately after the laser pulse is approximately the same in each case, and the ortho phonon-assisted recombination rate does not depend on stress.

Table 1 shows the rate parameters deduced from these fits at 2 K. The standard deviations of the parameters are generally small because each set of parameters represents a single fit to six data sets, the ortho and para data at three different densities. The uncertainty in the measurement of the stress is approximately 0.1 kbar. Since the exciton volume does not depend strongly on the applied stress, this study indicates that the Auger rate increases...
roughly as the square of the stress. The relative values of the $A_o$ and $A_p$ for different stresses are tightly constrained by these fits, but the absolute values are uncertain within a factor of two because of the uncertainty in the absolute density of the excitons. Setting the absolute magnitudes of the Auger coefficients requires an estimate of the absolute exciton density in the strain well, which is done by the same process as previously reported [9]. The present results are consistent with a previous study [9] which gave a value of approximately $10^{-16}$ cm$^3$/ns for both $A_o$ and $A_p$ at 2.5 kbar. The average relative number of 0.001 for the Auger constants at 2.5 kbar should therefore be equated with this absolute value.

As mentioned above, some authors [6,22] have proposed that two orthoexcitons can convert rapidly to two paraexcitons by a collisional process. We cannot strictly rule out this process, but find it is not necessary to invoke this process to fit the data. It is not possible to fit the data at high stress without an Auger process. The Auger process shows up in two important ways. First, the paraexciton rise time is shorter at high density than at low density, as shown in Figs. 3(b) and 6(b). This happens because as the paraexciton density increases, the inflow is counteracted by increasing outflow due to Auger recombination. A second effect is that extra orthoexcitons are generated by up-conversion from paraexcitons, which leads to a slowing of the ortho decay at late times at high density. This effect of up-conversion from paraexcitons to orthoexcitons in the strain well has been reported before [21].

In general, it is not possible to prove that no other processes besides those included in the rate equations (5) can exist. We can only say that these equations fit the data well over a wide range of density, temperature and stress, and this lends strong support to the existence of a stress-dependent Auger effect.

V. SURFACE EFFECTS?

The fact that we do not see evidence for an Auger effect at 1.5 kbar is surprising, since previous authors have reported evidence for an Auger effect at zero stress [8,23]. One possible
difference is that those experiments involved excitation of the surface of the crystal, using light absorbed within 25 microns of the surface. The presence of the surface may change the local symmetry enough to cause an Auger effect.

We have verified that an Auger effect must occur in surface excitation with zero stress. Fig. 10 shows the orthoexciton luminescence intensity for high temperature (300 K) excitation, with negligible applied stress. The absorption length of the 600 nm laser at this temperature is approximately 10 $\mu$m, which effectively confines the excitons to a region near the surface, as in the case of 514 nm excitation at low temperature. At room temperature, the orthoexcitons and paraexcitons are strongly coupled by phonon absorption and emission; therefore the orthoexciton decay gives the total decay of the two species of excitons. As seen in this figure, the excitons decay more rapidly at high density, indicating a density-dependent process as expected for an Auger process. A spin-flip mechanism as suggested by Ref. [6] would not give this behavior, since it conserves the total number of excitons. Yet at low stress in the well, we did not see any evidence for an Auger process. One possible explanation is that the density is much higher in the case of surface excitation.

We do not have any direct measurement of the depth of the region of the crystal excited by the laser, but estimating a depth of 10 $\mu$m based on the reported absorption constant, and a laser spot diameter of 200 $\mu$m, the density of the excitons in this case should be lower than in the strain well trap measurements discussed above. Another possible explanation is that the surface plays a role in the Auger effect. Many processes, such as second harmonic generation, are forbidden in the bulk of a centrosymmetric crystal like Cu$_2$O but are allowed near a surface.

At late times the orthoexciton luminescence fits a single-exponential decay with a lifetime of 350 ns, consistent with earlier results [10]. Since the orthoexcitons and paraexcitons are well coupled, this is also a lower bound for the paraexciton nonradiative decay lifetime. At low temperature, we found a paraexciton decay rate of around 20 ns, as discussed in Section IV, which cannot be the case here. Presumably, the paraexcitons can only become bound to impurities at low temperature, and therefore do not decay by that mechanism at room
This 350 ns lifetime does give a lower bound on the radiative recombination rate at low temperature. At higher temperature, the direct single-photon recombination process for orthoexcitons is nearly forbidden, but the phonon-assisted process is not strongly affected by temperature. The phonon-assisted radiative recombination process cannot occur with a lifetime less than 350 ns, based on these measurements. At low temperature, the total direct recombination luminescence intensity is approximately the same as that of the phonon-assisted recombination luminescence. Therefore, even at low temperature, the radiative recombination lifetime of the orthoexcitons cannot be less than around 100 ns. The paraexciton phonon-assisted radiative lifetime is known from absorption experiments to be 500 times longer than the orthoexciton radiative lifetime. As stress is increased, the paraexciton radiative lifetime becomes shorter, but the total paraexciton direct recombination luminescence intensity does not exceed the orthoexciton direct recombination luminescence intensity, which implies that the paraexciton radiative lifetime must also be on the order of 100 ns even at high stress.

VI. CONCLUSIONS

Previous experiments have concentrated on seeking BEC of excitons in Cu$_2$O in one of two types of experiments—either with intense surface excitation, or in harmonic-potential traps made with high stress. These results indicate that searches for BEC may be best pursued in a trap with fairly low stress. With surface excitation, surface effects may shorten the lifetime of the excitons. At high stress, the Auger recombination rate seems to increase, and the orthoexciton conversion to paraexcitons gets slower. Both of these effects inhibit Bose condensation in the exciton ground state. If excitons are created as orthoexcitons, then at high stress they will remain in that state longer, instead of converting into the lower paraexciton state, where we would like to accumulate the condensate.

The problem with pursuing BEC of excitons at low stress is that the orthoexciton lu-
minescence line substantially overlaps the paraexciton line in energy, which is also weaker since the paraexciton line is forbidden at zero stress. This makes analysis of the spectral lines difficult. One obvious solution is to not create orthoexcitons. This is not so simple, because the paraexciton absorption is very weak, and therefore most experiments have used the strong phonon-assisted orthoexciton absorption. A way around this is to use resonant two-photon generation of paraexcitons. Experiments with this approach are under way.

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|                | 1.5 kbar       | 2.5 kbar       | 3.5 kbar       |
|----------------|----------------|----------------|----------------|
| $\tau_{o-p}$ (ns) | 3.2 ±0.1       | 4.9 ±0.03      | 9.4 ±0.06      |
| $\tau_p$ (ns)     | 14.6 ±0.3      | 15.2 ±0.2      | 19.4 ±0.3      |
| $A_o$ (relative units) | 0.00046 ±0.00001 | 0.0015 ±0.00002 | 0.003 ±0.00004 |
| $A_p$ (relative units) | 0.000136 ±0.000005 | 0.00074 ±0.00002 | 0.0038 ±0.0001  |
| $R_p$            | 0.0142 ± 0.0007 | 0.047 ± 0.0007 | 0.186 ± 0.002  |

**TABLE I.** Fit values from least-squares fits of the data sets to the theory discussed in the text.
FIGURE CAPTIONS

FIG 1. Decay of the orthoexciton phonon-assisted luminescence at three different stresses, under identical excitation conditions.

FIG 2. Solid circles: lifetime of the orthoexciton phonon-assisted luminescence at low density as a function of the ortho-para energy splitting. Open circle: lifetime of the orthoexcitons at zero stress, reported by Weiner et al. [20]. Solid line: fit to the theory discussed in the text. Inset: the relative energies of the orthoexciton (upper level), paraexciton (lower level) and acoustic phonons involved in the conversion process.

FIG 3. Ortho and para luminescence decay in the strain well for the case $T = 2$ K, 3.5 kbar stress, and 100 mW average laser power. (a) Open circles: intensity of the orthoexciton phonon-assisted luminescence as a function of time following the laser pulse. Solid line: fit to the theory discussed in the text. (b) Open circles: intensity of the paraexciton direct recombination luminescence as a function of time. Solid line: fit for the same theory as (a).

FIG 4. Ortho and para luminescence decay in the strain well, as in Fig. 3, but for the case $T = 2$ K, 3.5 kbar stress, and 10 mW average laser power.

FIG 5. Full width at half maximum (FWHM) of the orthoexciton phonon-assisted luminescence spectrum for the same data used in Figs. 3 and 4. Solid lines: the FWHM in each case implied by the temperature used in the orthoexciton down-conversion rate of the fits to the data of Figs. 3 and 4.

FIG 6. Ortho and para luminescence decay in the strain well, as in Fig. 3, but for the case $T = 2$ K, 2.5 kbar stress, and 100 mW average laser power.
FIG 7. Ortho and para luminescence decay in the strain well, as in Fig. 3, but for the case $T = 2$ K, 2.5 kbar stress, and 10 mW average laser power. (At late times, the orthoexciton luminescence hits the dark count rate, and this dark count rate is included in the fit as an additive constant of 0.01.)

FIG 8. Ortho and para luminescence decay in the strain well, as in Fig. 3, but for the case $T = 2$ K, 1.5 kbar stress, and 100 mW average laser power. At early times the orthoexciton luminescence obscures the paraexciton luminescence.

FIG 9. Ortho luminescence decay in the strain well for the case $T = 2$ K, 1.5 kbar stress, and three different laser powers. Circles: 1 mW. Squares: 10 mW. Diamonds: 100 mW.

FIG 10. Orthoexciton luminescence decay at $\lambda = 629$ nm for surface excitation at $\lambda = 602$ nm, at room temperature and zero stress, for two laser powers. The two curves are normalized to the same initial value. The laser focus spot size was approximately 200 $\mu$m.
(a) and (b) show plots of intensity (counts/s) versus time (t, ns) with logarithmic scales on both axes.
