Particle correlations and evidence for dark state condensation in a cold dipolar exciton fluid

Yehiel Shilo\textsuperscript{1}, Kobi Cohen\textsuperscript{1}, Boris Laikhtman\textsuperscript{1}, Ken West\textsuperscript{2}, Loren Pfeiffer\textsuperscript{2} & Ronen Rapaport\textsuperscript{1,3}

Dipolar excitons are long-lived quasi-particle excitations in semiconductor heterostructure that carry an electric dipole. Cold dipolar excitons are expected to have new quantum and classical multi-particle correlation regimes, as well as several collective phases, resulting from the intricate interplay between the many-body interactions and their quantum nature. Here we show experimental evidence of a few correlation regimes of a cold dipolar exciton fluid, created optically in a semiconductor bilayer heterostructure. In the higher temperature regime, the average interaction energy between the particles shows a surprising temperature dependence, which is evidence for correlations beyond the mean field model. At a lower temperature, there is a sharp increase in the interaction energy of optically active excitons, accompanied by a strong reduction in their apparent population. This is evidence for a sharp macroscopic transition to a dark state, as has been suggested theoretically.
Different collective many-body effects in Bose quantum fluids of atoms and exciton-polaritons have been observed in recent years. The common feature of these quantum fluids is the weak interaction between the particles, which generally can be well described using mean field theories, where the interaction is considered as a local, contact-like scattering. In contrast, cold dipolar fluids are composed of particles that carry a permanent electric dipole. Owing to the strength and longer range of the dipole–dipole interaction, dipolar fluids are predicted to display physics that goes beyond a mean field description. In particular, cold dipolar bosons are expected to have new quantum as well as classical multi-particle correlation regimes. Observing the many-body correlations will open a window to the complex underlying physics that may drive the fluid into different theoretically proposed collective phases such as dipolar superfluids, dipolar crystals and dipolar liquids.

There are currently only a few feasible realizations of quantum dipolar fluids that are being experimentally tested. Perhaps the most known are dipolar atoms or polar molecules in either magneto-optical traps or optical lattices, and indirect dipolar excitons in semiconductor quantum structures. Indirect dipolar excitons (X_{id}) are coulomb-bound electron-hole pairs inside an electrically gated semiconductor bilayer (also known as a double quantum well (DQW)). X_{id} are two-dimensional (2D) boson-like quasi-particles (see illustration in Fig. 1a) with four quasi degenerate spin states (in GaAs based DQW structures). The two states with spin S = ±1 are optically active (‘bright’) and the two states with spin S = ±2 are optically inactive (‘dark’). The X_{id} carry a static electric dipole because of the separation of the electron and the hole into the two adjacent layers. Furthermore, all the dipoles are aligned perpendicular to the layers, so that the dominant interaction between the X_{id} is an extended repulsive dipole–dipole interaction. The unique advantage of X_{id} systems is that the effect of the interactions between the excitons can be observed directly: the interaction of a given exciton with its surrounding excitons is manifested in an excess energy (called the ‘blue shift’ – ΔE), carried away from the system by a photon as the exciton recombines radiatively. It was suggested theoretically that this observed interaction energy could be used as a direct experimental probe of the various particle correlation regimes and the thermodynamic phases of X_{id} systems, if it can be mapped as a function of the fluid temperature and density. However, calibrating the fluid density reliably at different temperatures turned out to be a non-trivial task in optically excited exciton systems, which so far hindered direct and consistent observations of interaction-induced particle correlations. On the other hand, recent works have shown other manifestations of a spontaneous transition to a macroscopic condensed state of X_{id} such as an extended optical coherence of the X_{id} emission, as well as persistent spin textures in excitonic rings.

In this paper, we show experimental evidence of a few correlation regimes of a cold dipolar exciton fluid, created optically in a semiconductor bilayer heterostructure. In the higher temperature regime, the average interaction energy between the particles shows a temperature dependence that is an evidence for correlations beyond the mean field model. At a lower temperature, there is a sharp increase in the interaction energy of optically active excitons, which is accompanied by a strong reduction in their apparent population. This could be an evidence for a sharp macroscopic transition, where the fluid redistribute its density with dark states that are uncoupled to light, as was suggested theoretically.

Results

Experimental scheme. Here we present time-resolved photoluminescence (PL) experiments of an optically excited X_{id} fluid.
trapped inside an electrostatic trap\textsuperscript{23–26}. We extract a consistent mapping of \(\Delta E\) for a range of bright exciton densities \((n_b)\) and temperatures. Figure 1b,c show typical time-resolved PL images of an \(X_{id}\) fluid inside an electrostatic trap after its excitation with a non-resonant-pulsed laser. About 50 ns after excitation, the fluid reaches a dynamic equilibrium between the dipole–dipole repulsion of excitons that tends to drive the fluid outwards, and the confining ‘flat well’ potential induced by the electrostatic gate\textsuperscript{27}. This equilibrium results in a uniform and homogeneous PL distribution inside the trap, indicating a flat density profile. This is clearly seen in Fig. 1c,d,e present the the corresponding spatial-spectral images taken along the central axis of the trap gate. Figure 1e shows that the homogeneously distributed PL is blue shifted from the emission energy of a single exciton. This positive blue shift energy \(\Delta E_{id}\) is due to the repulsive dipole–dipole interaction inside the \(X_{id}\) fluid. In general, \(\Delta E\) increases as \(n_b\) increases and its value is sensitive to the intricate multi-particle correlation\textsuperscript{5,15}.

### Analysis of the \(X_{id}\) lifetime

Figure 2a presents an example of the spatially integrated and normalized PL spectra, taken at \(T = 3\) K at different times after the excitation pulse. The spectral position of the PL line shifts with time to lower energies as \(n_b\) decreases. At long times, the PL energy asymptotically reaches a constant value. The difference between the PL energy at any given time to this asymptotic value is the blue shift energy \(\Delta E\) (marked by the arrow in Fig. 2a). The time dependence of the spectrally integrated PL intensity \((I)\) and \(\Delta E\) are plotted in Fig. 2b. As the \(X_{id}\) density drops with time, both \(I\) and \(\Delta E\) decreases with a non-exponential decay rate. The reason for this non-exponential decay is the dependence of the \(X_{id}\) radiative recombination time \((\tau_{id})\) on \(n_b\) as is illustrated in Fig. 3a. Radiative recombination of the \(X_{id}\) can be described by a tunnelling of either the electron or the hole (with a much lower probability because of its larger mass) to the adjacent well, where direct optical recombination with the oppositely charged particle takes place with a direct exciton recombination time \(\tau_d\). The tunnelling probability depends on the difference between the direct and indirect transition energies, \(E_d - E_{id}\). The larger the energy difference, the larger the \(\tau_{id}\) compared with \(\tau_d\). This picture can be quantified to get an expression for \(\tau_{id}\) in terms of \(\tau_d\) and \(E_d - E_{id}\) (see Supplementary Note 1):

\[
\frac{1}{\tau_{id}} = \frac{1}{\tau_d} + \frac{\nu^2}{(E_d - E_{id})^2}
\]

where \(|\epsilon|^2\) is the probability for an electron to tunnel to the hole QW, and \(\nu\) is the tunnelling matrix element. Note that although the non-polar, direct transition energy \(E_d\) is independent of density, the dipolar energy \(E_{id}\) depends on \(n_b\). The time dependence of \(\tau_{id}/\tau_d\) can be extracted from equation (1) by plugging in it the experimental values of \(E_d - E_{id}(t)\). Figure 2b presents this time dependence for the two exemplary temperatures of 1.9 and 5 K.

### Density calibration and thermal distribution of the \(X_{id}\) fluid

Because the dominant \(X_{id}\) recombination channel is radiative\textsuperscript{21,22,28}, the dynamics, and its relation to the observed PL intensity, can be described by a simple rate equation. Assuming an equilibrium of bright and dark \(X_{id}\) with equal densities\textsuperscript{29} (that is, \(n_b = n_d\) where \(n_d\) is the dark \(X_{id}\) density), we get:

\[
I(t) = - \beta(T) \frac{d}{dt}(n_b(t) + n_d(t)) = -2\beta(T) \frac{dn_b(t)}{dt}
\]

where \(n_{rad}\) is the density of optically active excitons with in-plane k-vectors that are inside the radiation light cone, \(\beta(=n_{rad}/n_b)\), and \(\alpha(T)\) is the fraction of the total emitted photon flux that is collected by the detector (see Piermarocchi et al.\textsuperscript{30} and Supplementary Note 2 for more information). We now note that counting all the emitted photons from a given time \(t\) after the excitation to \(t \rightarrow \infty\) (where \(n_b = 0\) yields \(n_b(t)\), that is,

\[
n_b(t) = \int_{t}^{\infty} I(t')dt'.
\]

Combining equation (2) with equation (3), we get a relation between \(I(t)\), \(\tau_{id}(t)\) and \(\beta(T)\):

\[
I(t) = \frac{\beta(T,t) \int_{t}^{\infty} I(t')dt'}{2\tau_{id}(t)}
\]

As \(\tau_{id}\) was extracted independently from the PL energy using equation (1), comparing the two sides of the equation yields \(\beta(T,t)\). This dependence is plotted for three different temperatures in Fig. 3d. \(\beta\) increases with decreasing time, that is, with increasing \(n_b\). Also, \(\beta\) decreases with temperature. This density dependence is a signature of a deviation from a pure classical ideal gas distribution. Figure 3e plots the theoretically calculated values of \(\beta(n_b)\) for the three corresponding temperatures using an ideal 2D Bose–Einstein (BE) model (see Supplementary Note 2 for the full derivation). There is a reasonable qualitative agreement between the calculation and the experiment, indicating the validity of the model assumptions. However, it is noteworthy that currently we cannot obtain a direct comparison between the theoretical and
experimental values of $\beta$, as no absolute measurement of $n_b$ exists. Another strong verification for the validity of the above analysis was done for a trapped $X_{id}$ fluid in a steady state under a non-resonant continuous wave laser excitation and is shown in Supplementary Note 3.

Evidence for correlations in the $X_{id}$ fluid. Figure 4a shows in green circles the temperature dependence of $\beta$ at the high-density limit (marked by the black dashed lines in Fig. 3d). $\beta(T)$ increases as $T$ decreases down to $\sim 2.5$ K, where it suddenly drops. This behaviour is fitted to an ideal BE distribution, shown by the solid blue line. For temperatures above $\sim 2.5$ K, the theoretical prediction fits well with the experimental data. This means that for $T \gtrsim 2.5$ K, the $X_{id}$ fluid has a well-defined thermal distribution, but sharply deviates from it at lower temperatures. This is the first important observation of this analysis.

Next, we would like to map the dependence of $\Delta E$ on $T$ and $n_b$. This can be done with a common experimental calibration for the optically active exciton densities for all temperatures using equation (3). To do this in a simple tractable manner, we calculate an approximate, density independent value of $\beta(T)$. We can then use this calculated value with equation (3) and the experimental values of $I(t)$ to get $n_b(t)$ for each $T$. The results are plotted in Fig. 3c. This procedure allows us to compare the behaviour of the $X_{id}$ fluid with similar densities but at different temperatures.

Figure 4b presents the experimental dependence of $\Delta E$ on $T$ for different fixed densities. Two distinct temperature regimes are observed for all densities, corresponding exactly to the two regimes seen for $\beta(T)$, with a sharp transition between them at $T_\text{c} \approx 2.5$ K. For all temperatures above $T_\text{c}$, a clear temperature dependence of $\Delta E$ is observed. $\Delta E$ decreases with decreasing $T$. This dependence is a clear evidence for particle correlations beyond mean field. In contrast, a mean field calculation of $\Delta E$ predicts a ‘capacitor formula’ dependence that is temperature independent.$^{31}$ As the dipole–dipole interaction between the excitons is repulsive, a reduction of $\Delta E$ for a given density $n_b$ means an increase in the particle correlations: the more the $X_{id}$ spatially correlate to minimize their energy, the smaller $\Delta E$ will be. Therefore, the results suggest that as $T$ decreases, the spatial correlations of the excitons in the fluid increase. To better quantify the dependence of $\Delta E$ and therefore the particle correlations on $n_b$ and $T$ in this regime, we look for a scaling law of our data. Figure 5a plots $\Delta E$ for a large set of densities and for all the measured temperatures above, as a function of $n_b T^2$. The data collapse into a single linear line to a high accuracy (see inset). The linear dependence of $\Delta E$ on $n_b$ suggests a lack of long range order in the fluid.$^{5}$ The scaling of $\Delta E$ on $T^2$ is surprising. In contrast, the models of Laikhtman and Rapaport, and Schindler and Zimmermann$^{15}$ predict a much weaker, sublinear dependence of $\Delta E$ on $T$, if the dipoles are a classically correlated gas. This specific temperature dependence could be an indication for a transition of the fluid correlations from classical to quantum. Although the former are expected to lead to a clear temperature dependence of $\Delta E$, the latter should have a much weaker dependence, as was calculated in Laikhtman and

![Figure 3](image-url) | Density calibration and thermal distribution of the $X_{id}$ fluid. (a) On the left side, a schematic illustration of the energy band diagram of a DQW (in the growth direction) under an applied bias is shown. The energies of the direct exciton ($E_d$) and the dipolar exciton ($E_{id}$) are marked. The right side illustrates the process of an $X_{id}$ optical recombination in which the electron effectively tunnels to the adjacent well (stage 1) and recombines with the hole (stage 2), emitting a photon. (b) Extracted $\tau_d/\tau_{id}$ versus time for two experimental temperatures $T = 1.9$ and $5$ K, using equation (1). (c) The bright exciton density, $n_b(t)$, as a function of time for different temperatures, extracted using the calibration procedure described in the text. (d) The experimentally obtained values of $\beta$ at different times for three different temperatures. (e) Calculated values of $\beta$ as a function of $n_b$ for the same temperatures as in (d) using an ideal 2D BE thermal distribution.
Figure 4 | Particle correlation regimes of an $X_d$ fluid. (a) $\beta$ values at the high exciton density limit (marked by the black dashed lines in Fig. 3d), as a function of $T$ (green circles), the error bars are calculated from the data in Fig. 3d. The solid blue line is the theoretical values of $\beta$, assuming an ideal 2D BE thermal distribution with $n_b = 3.5 \times 10^{10}$ cm$^{-2}$. (b) $\Delta E$ as a function of $T$ for different values of bright exciton densities, $n_b$ (dashed lines are guides to the eye). The vertical black dashed line mark $T_c$, the boundary between the two regimes as is discussed in the text. A lower bound for $n_b$ can be obtained from the blue shift at the highest temperature by applying the mean field model, yielding $n_b \geq 2.2 \times 10^{10}$ cm$^{-2}$/a.u. For this density estimate, we assume that at the highest temperature, the bright and dark exciton densities are identical, and therefore $n_b$ is half of the total particle density.

Evidence for $X_d$ density redistribution in dark states. Turning to the other regime, we observe a sharp increase in $\Delta E$ for all densities just below $T_c$. This jump correlates well with the onset of the deviation from the theoretical values of $\beta$ plotted in Fig. 4a, where we observe a sharp drop of $\beta(T < T_c)$ with much less radiative $X_d$ than the theoretical prediction of a BE gas of bright excitons (plotted in blue). In other words, suddenly below $T_c$, there seem to be less bright excitons but yet more interaction energy. This could be an indication for a sudden and sharp depletion of the bright exciton density and a sudden macroscopic transition to an optically inactive ‘dark’ state below $T_c$. This increase in the density of the dark state can be seen in $\Delta E$ of bright excitons, as these dark excitons still interact with the bright excitons. A BE condensation (BEC) of dark excitons and its effect on the excited bright exciton energy was recently suggested in a theoretical paper by Combescot et al. It was proposed that in perfect excitonic systems, the dark excitons should have an energy slightly lower than the bright excitons, and therefore at low enough temperatures and high densities, a BEC should form in the dark state. The following possible scenario is therefore consistent with our experimental observations: for all temperatures, the pulse excitation creates a large density of hot particles that very quickly (within a few nanoseconds) cool down to the lattice temperature. For $T > T_c$, due to efficient spin flip processes between dark and bright states, their population is approximately equal throughout the optical recombination process and their density decay together with time (that is, $n_b(t) = n_d(t)$ for all $t$). At temperatures below $T_c$, the high-density fluid cools down and condenses fast after excitation, pulling bright excitons to the dark ground state so that the population equality between the two species breaks down, resulting in more dark excitons and less bright excitons than expected ($n_b < n_d$), as is seen in Fig. 4a,b. The fact that the temperature dependence of this transition is very sharp (a fraction of a Kelvin), excludes the possibility of a simple thermal re-population of a lower dark state, but rather indicates to a sharp macroscopic transition.

Discussion

With the above picture in mind, it is expected that after the condensation, the scattering between the condensed particles in the fluid will be strongly suppressed, leading to a suppression of spin flip processes and therefore to an effective decoupling of the dark $X_d$ from the bright ones. An evidence for spin-scattering suppression was recently observed and analysed theoretically.

As the condensation and the bright–dark decoupling happens shortly after the pulse excitation, it should be hard to directly
observe the existence of a dark state by monitoring the dynamics of the bright $X_{id}$ PL intensity alone. However, there is a way to probe the dark state existence, as can be seen from Fig. 5b. Here we plot the time dependence of the energy ‘jump’ given by $\delta E(t) = E_{id}(t, T = 2.2 K) - E_{id}(t, T = 2.6 K)$, where these two temperatures correspond to the temperatures just below and above $T_c$ respectively. It can be seen that $\delta E$ persists for times much longer than even the longest bright exciton lifetime (marked by the red dashed line), which indicates that there is a dark long-lived state in the system affecting the energy of the bright $X_{id}$ via mutual dipolar interactions. This observation is consistent with a dark excitonic state.

A darkening of the PL of $X_{id}$ in a centre of stress-induced trap was recently observed by Sinclair et al. 33 In that work, the observed darkening was successfully explained by a position-dependent mixing of light- and heavy-hole $X_{id}$, which differ in energy. This mixing was induced by the inhomogeneous strain along the trap cross-section, and is essentially a single-particle effect, in contrast to a collective many-body effect. Their explanation did not, however, account for the temperature-dependent onset of their observed darkening. Therefore, it was suggested in Sinclair et al. 33 that perhaps many-body effects, and in particular dark–bright exciton splitting and dark exciton BEC, could be also involved; however, these effects could not be isolated. As the same strain fields are also expected to mix bright and dark excitons, it further complicates the interpretation. In our experiments, the trap is electrostatic, with a flat homogeneous electric field distribution all across the trap. In order to prevent a significant charge separation that can occur on the boundary of the trap, 23, 24, 35 the DQW structure is placed much closer to the bottom electrode than to the top gates in order to prevent a significant charge separation that can occur on the boundary of the trap. 23, 24, 35

**Experimental setup.** The sample is mounted into a liquid He optical cryostat (Jania). The sample temperature in these experiments was varied in the range of 1.3–7 K. The sample is excited non-resonantly with a 671-nm Q-switched laser with a pulse duration of 15 ns and a repetition rate of 25 kHz, focused on the centre of the trap gate. The time and spatially resolved images following the excitation pulses are collected by a fast-gated intensified CCD camera (PIMAX-II) mounted on a spectrometer (Princeton Instruments).

**Methods**

**Sample.** The sample that is used in the experiment is a bilayer structure consisting of a 120/40/120Å—GaAs/Al$_{0.4}$Ga$_{0.6}$As/GaAs DWQ on top of a n-doped GaAs substrate grown by molecular beam epitaxy. The bilayer structure consists, which serves as a bottom electrode. A semi-transparent metallic Ti circular electric gate, with a 50-μm diameter, is micro-fabricated on top of the structure and is connected to a top electrode, as illustrated in Fig. 1a. The area of the circular gate forms an electrostatic trap for the $X_{id}$, which remain confined under it. The DQW structure is placed much closer to the bottom electrode than to the top gates in order to prevent a significant charge separation that can occur on the boundary of the trap. 23, 24, 35

**References**

1. Bloch, I., Dalibard, J. & Zwerger, W. Many-body physics with ultracold gases. *Rev. Mod. Phys.* 80, 885–964 (2008).
2. Deng, H., Haug, H. & Yamamoto, Y. Exciton-polariton Bose-Einstein condensation. *Rev. Mod. Phys.* 82, 1489–1537 (2010).
3. Lahaye, T., Menotti, C., Santos, L., Lewenstein, M. & Pfau, T. The physics of dipole-dipole interacting quantum gases. *Rep. Prog. Phys.* 72, 126401 (2009).
4. Papilo, G., Mischel, A., Boninesegni, M., Lesanovsky, I. & Zoller, P. Strongly correlated gases of rydberg-dressed atoms: quantum and classical dynamics. *Phys. Rev. Lett.* 104, 230002 (2010).
5. Laikhtman, B. & Rapaport, R. Exciton correlations in coupled quantum wells and their luminescence blue shift. *Phys. Rev. B* 80, 195313 (2009).
6. Astrakharchik, G. E., Boronat, J., Kurbakov, I. L. & Lozovik, Y. E. Quantum phase transition in a two-dimensional system of dipoles. *Phys. Rev. Lett.* 98, 060405 (2007).
7. Büchner, H. P. et al. Strongly correlated 2d quantum phases with cold polar molecules: Controlling the shape of the interaction potential. *Phys. Rev. Lett.* 98, 060404 (2007).
8. Böning, J., Filinov, A. & Bonitz, M. Crystallization of an exciton superfluid. *Phys. Rev. B* 84, 075130 (2011).
9. Berman, O. L., Kezerashvili, R. Y. & Ziegler, K. Superfluidity of dipole excitons in the presence of band gaps in two-layer graphene. *Phys. Rev. B* 85, 035418 (2012).
10. Carr, L. D., DeMille, D., Krems, R. V. & Ye, J. Cold and ultracold molecules: science, technology and applications. *New J. Phys.* 11, 055049 (2009).
11. Eisenstein, J. P. & MacDonald, A. H. Bose-Einstein condensation of excitons in bilayer electron systems. *Nature* 432, 691–694 (2004).
12. High, A. A. et al. Spontaneous coherence in a cold exciton gas. *Nature* 483, 584–588 (2012).
13. Combescot, M., Berbered-Matibet, O. & Combescot, R. Bose-Einstein condensation in semiconductors: the key role of dark excitons. *Phys. Rev. Lett.* 99, 176403 (2007).
14. Lee, R. M., Drummond, N. D. & Needs, R. J. Exciton-exciton interaction and biexciton formation in bilayer systems. *Phys. Rev. B* 79, 125308 (2009).
15. Schindler, C. & Zimmermann, R. Analysis of the exciton-exciton interaction in semiconductor quantum wells. *Phys. Rev. B* 78, 045313 (2008).
16. Stern, M. et al. Photoluminescence ring formation in coupled quantum wells: excitonic versus ambipolar diffusion. *Phys. Rev. Lett.* 101, 257402 (2008).
17. Vörös, Z., Smoke, D. W., Pfeifer, K. L. & West, K. Direct measurement of Exciton-Exciton Interaction Energy. *Phys. Rev. Lett.* 103, 016403 (2009).
18. Cohen, K., Rapaport, R. & Santos, P. V. Remote dipolar interactions for objective density calibration and flow control of excitonic fluids. *Phys. Rev. Lett.* 106, 126402 (2011).
19. High, A. A. et al. Condensation of excitons in a trap. *Nano Lett.* 12, 2605–2609 (2012).
20. Alliong, M., Fuster, D., Gonzalez, Y., Gonzalez, L. & Dubin, F. Observation of macroscopic coherence in self-organized dipolar excitons. Preprint at http://arxiv.org/abs/1210.3176 (2012).
21. Rapaport, R. et al. Charge separation of dense two-dimensional electron-hole gases: Mechanism for exciton ring pattern formation. *Phys. Rev. Lett.* 92, 117405 (2004).
22. Butov, L. V. et al. Formation mechanism and low-temperature instability of exciton rings. *Phys. Rev. Lett.* 92, 117404 (2004).
23. Rapaport, R. et al. Electrostatic traps for dipolar excitons. *Phys. Rev. B* 72, 075428 (2005).
24. Hammack, A. T. et al. Excitons in electrostatic traps. *J. Appl. Phys.* 99, 066104 (2006).
25. Schinner, G. J. et al. Electrostatically trapping indirect excitons in coupled InGaAs quantum wells. *Phys. Rev. B* 83, 165308 (2011).
26. Chen, G. et al. Artificial trapping of a stable high-density dipolar exciton fluid. *Phys. Rev. B* 74, 045309 (2006).
27. Rapaport, R., Chen, G. & Simon, S. Analysis of trapped quantum degenerate dipolar excitons. *Appl. Phys. Lett.* **89**, 152118 (2006).
28. Sivalertporn, K., Mouchlidis, I., Ivanov, A. L., Philp, R. & Muljarov, E. A. Direct and indirect excitons in semiconductor coupled quantum wells in an applied electric field. *Phys. Rev. B* **85**, 045207 (2012).
29. Maialle, M. Z., De Andrada e Silva, E. A. & Sham, L. J. Exciton spin dynamics in quantum wells. *Phys. Rev. B* **47**, 15776–15788 (1993).
30. Piermarocchi, C., Tassone, F., Savona, V., Quattropani, A. & Schwendimann, P. Exciton formation rates in GaAs/AlGaAs quantum wells. *Phys. Rev. B* **55**, 1333–1336 (1997).
31. Butov, L. V., Shashkin, A. A., Dolgopolov, V. T., Campman, K. L. & Gossard, A. C. Magneto-optics of the spatially separated electron and hole layers in GaAs/AlGaAs coupled quantum wells. *Phys. Rev. B* **60**, 8753–8758 (1999).
32. Leonard, J. R. *et al.* Spin transport of excitons. *Nano. Lett.* **9**, 4204–4208 (2009).
33. Sinclair, N. W. *et al.* Strain-induced darkening of trapped excitons in coupled quantum wells at low temperature. *Phys. Rev. B* **83**, 245304 (2011).
34. Hagn, M., Zrenner, A., Böhm, G. & Weimann, G. Electric-field-induced exciton transport in coupled quantum well structures. *Appl. Phys. Lett.* **67**, 232–234 (1995).
35. Kowalik-Seidl, K. *et al.* Tunable photoemission from an excitonic antitrap. *Nano. Lett.* **12**, 326–330 (2012).

**Acknowledgements**

We would like to thank Oded Agam, Paulo Santos and Snezana Lazic for useful discussions. Y.S., K.C. and R.R. acknowledge funding from the D.F.G. Project no. 581021 and by the Israeli Science Foundation Project no. 1319/12. The work at Princeton was partially funded by the Gordon and Betty Moore Foundation through Grant no. GBMF2719 and by the National Science Foundation MRSEC-DMR-0819860 at the Princeton Center for Complex Materials.

**Author contributions**

The experiments were carried out by Y.S. The experimental setup was built by Y.S. and K.C. Y.S. and R.R. analysed the data with a help from K.C. The samples were grown by L.P. and K.W. The expression for the indirect exciton lifetime was derived by B.L. The manuscript was prepared by Y.S. and R.R. with inputs from the other co-authors. R.R. planned and supervised the project.

**Additional information**

Supplementary Information accompanies this paper at http://www.nature.com/naturecommunications

Competing financial interests: The authors declare no competing financial interests.

Reprints and permission information is available online at http://npg.nature.com/reprintsandpermissions/

How to cite this article: Shilo, Y. *et al.* Particle correlations and evidence for dark state condensation in a cold dipolar exciton fluid. *Nat. Commun.* 4:2335 doi: 10.1038/ncomms3335 (2013).