(Fig. 3d–f) the nanocrystal orientations that are consistent with the spectra and polarizations in Fig. 3a–c. Again, good agreement is obtained.

In Fig. 3g we present the experimental statistics for one-, two- and three-line spectra. One is most common, suggesting that only the lowest sublevel is populated. For the two- and three-line spectra, the measured energy splittings are plotted in Fig. 3h, i. Given three sublevels separated by energies Δ_1 and Δ_2 (Fig. 3i, inset), the average splitting $\overline{\Delta}$ is $0.5(\overline{\Delta}_1 + \overline{\Delta}_2)$, with bars denoting averages. However, two-line spectra can involve any two of the three features, leading to the average $\overline{\Delta}_1/3 + \overline{\Delta}_2/3 + (\overline{\Delta}_1 + \overline{\Delta}_2)/3 = 2(\overline{\Delta}_1 + \overline{\Delta}_2)/3$. We therefore predict a ratio of 1.33 for average measured splittings in two- versus three-line spectra. The experimentally determined ratio of 1.42 ± 0.12 again supports our model.

While we have used cryogenic temperatures to confirm the existence of the bright triplet exciton, its influence on emission remains important at room temperature. Although the splittings are small compared to the thermal energy, the three triplet states (from four sublevels in total) are dipole-allowed and thermally populated, unlike in other nanocrystals[13–16]. For example, in CdSe nanocrystals only three of eight band-edge sublevels are bright, and these can be poorly populated even at room temperature. This and other effects (Supplementary Information section 5) explain why room-temperature emission from $CsPbX_3$ perovskite nanocrystals is 20 times faster than in other systems. The emission should be even faster for nanowires and nanoplatelets. Such shapes can further decrease the radiative lifetime, owing to diminished dielectric screening and smaller one- or two-dimensional excitons[30].

Although $CsPbX_3$ nanocrystals are oxidatively stable, their long-term stability may be limited in warm, bright and moist environments without encapsulation to provide thermal and environmental stability. Moreover, the discovery that their lowest exciton is bright reveals criteria for obtaining this phenomenon in other materials. Potential semiconductors should lack inversion symmetry, and one band edge should have *s* symmetry and the other *p*, with the latter affected by strong spin–orbit coupling such that $J_{e,h} = 1/2$. Finally, the Rashba coefficient for the electron and the hole must be non-zero with the same sign.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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1. Scholes, G. D. & Rumbles, G. Excitons in nanoscale systems. *Nat. Mater.* **5,** 683–696 (2006).
2. Hund, F. Concerning the interpretation of complex spectra, especially the elements scandium to nickel. *Z. Phys.* **33,** 345–371 (1925).
3. Onodera, Y. & Toyozawa, Y. Excitons in alkali halides. *J. Phys. Soc. Jpn* **22,** 833–844 (1967).
4. Nirmal, M. *et al.* Observation of the "dark exciton" in CdSe quantum dots. *Phys. Rev. Lett.* **75,** 3728–3731 (1995).
5. Bychkov, Yu. A. & Rashba, E. I. Oscillatory effects and the magnetic susceptibility of carriers in inversion layers. *J. Phys. C* **17,** 6039–6045 (1984).
6. Kim, M., Im, J., Freeman, A. J., Ihm, J. & Jin, H. Switchable $S=1/2$ and $J=1/2$ Rashba bands in ferroelectric halide perovskites. *Proc. Natl Acad. Sci. USA* **111,** 6900–6904 (2014).
7. Zheng, F., Tan, L. Z., Liu, S. & Rappe, A. M. Rashba spin–orbit coupling enhanced carrier lifetime in $CH_3NH_3PbI_3$. *Nano Lett.* **15,** 7794–7800 (2015).
8. Kepenekian, M. *et al.* Rashba and Dresselhaus effects in hybrid organic–inorganic perovskites: from basics to devices. *ACS Nano* **9,** 11557–11567 (2015).
9. Mosconi, E., Etienne, T. & De Angelis, F. Rashba band splitting in organohalide lead perovskites: bulk and surface effects. *J. Phys. Chem. Lett.* **8,** 2247–2252 (2017).
10. Isarov, M. *et al.* Rashba effect in a single colloidal $CsPbBr_3$ perovskite nanocrystal detected by magneto-optical measurements. *Nano Lett.* **17,** 5020–5026 (2017).
11. Protesescu, L. *et al.* Nanocrystals of cesium lead halide perovskites ($CsPbX_3$, X=Cl, Br, and I): novel optoelectronic materials showing bright emission with wide color gamut. *Nano Lett.* **15,** 3692–3696 (2015).
12. Rainò, G. *et al.* Single cesium lead halide perovskite nanocrystals at low temperature: fast single-photon emission, reduced blinking, and exciton fine structure. *ACS Nano* **10,** 2485–2490 (2016).
13. Crooker, S. A., Barrick, T., Hollingsworth, J. A. & Klimov, V. I. Multiple temperature regimes of radiative decay in CdSe nanocrystal quantum dots: Intrinsic limits to the dark-exciton lifetime. *Appl. Phys. Lett.* **82,** 2793–2795 (2003).
14. Wuister, S. F., van Houselt, A., de Mello Donegá, C., Vanmaekelbergh, D. & Meijerink, A. Temperature antiquenching of the luminescence from capped CdSe quantum dots. *Angew. Chem. Int. Ed.* **43,** 3029–3033 (2004).
15. Du, H. *et al.* Optical properties of colloidal PbSe nanocrystals. *Nano Lett.* **2,** 1321–1324 (2002).
16. Bischof, T. S., Correa, R. E., Rosenberg, D., Dauler, E. A. & Bawendi, M. G. Measurement of emission lifetime dynamics and biexciton emission quantum yield of individual InAs colloidal nanocrystals. *Nano Lett.* **14,** 6787–6791 (2014).
17. Shirasaki, Y., Supran, G. J., Bawendi, M. G. & Bulović, V. Emergence of colloidal quantum-dot light-emitting technologies. *Nat. Photon.* **7,** 13–23 (2013).
18. Dang, C. *et al.* Red, green and blue lasing enabled by single-exciton gain in colloidal quantum dot films. *Nat. Nanotechnol.* **7,** 335–339 (2012).
19. Kim, T. H. *et al.* Full-colour quantum dot displays fabricated by transfer printing. *Nat. Photon.* **5,** 176–182 (2011).
20. Bir, G. L. & Pikus, G. E. *Symmetry and Strain-Induced Effects in Semiconductors* Ch. 23 (Wiley, 1974).
21. Even, J., Pedesseau, L., Jancu, J.-M. & Katan, C. Importance of spin–orbit coupling in hybrid organic/inorganic perovskites for photovoltaic applications. *J. Phys. Chem. Lett.* **4,** 2999–3005 (2013).
22. Kane, E. O. in *Semiconductors and Semimetals* Vol. 1 (eds Willardson, R. K. & Beer, A. C.) 75–100 (Academic Press, 1966).
23. Koster, G. F., Dimmock, J. O., Wheeler, R. G. & Statz, H. *Properties of the Thirty-Two Point Groups* (MIT Press, 1963).
24. Yaffe, O. *et al.* Local polar fluctuations in lead halide perovskite crystals. *Phys. Rev. Lett.* **118,** 136001 (2017).
25. Galland, C. *et al.* Two types of luminescence blinking revealed by spectroelectrochemistry of single quantum dots. *Nature* **479,** 203–207 (2011).
26. Cottingham, P. & Brutchey, R. L. On the crystal structure of colloidally prepared $CsPbBr_3$ quantum dots. *Chem. Commun.* **52,** 5246–5249 (2016).
27. Rashba, E. I. & Gurgenishvili, G. E. Edge absorption theory in semiconductors. *Sov. Phys. Solid State* **4,** 759–760 (1962).
28. Dery, H. & Song, Y. Polarization analysis of excitons in monolayer and bilayer transition-metal dichalcogenides. *Phys. Rev. B* **92,** 125431 (2015).
29. Fu, M. *et al.* Neutral and charged exciton fine structure in single lead halide perovskite nanocrystals revealed by magneto-optical spectroscopy. *Nano Lett.* **17,** 2895–2901 (2017).
30. Rodina, A. V. & Efros, Al. L. Effect of dielectric confinement on optical properties of colloidal nanostructures. *J. Exp. Theor. Phys.* **122,** 554–566 (2016).

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