Experimental certification of millions of genuinely entangled atoms in a solid

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Quantum theory predicts that entanglement –the paradigmatical quantum effect, now routinely observed in microscopic experiments– can also persist in macroscopic physical systems, albeit difficulties to demonstrate it experimentally remain. Beyond the fundamental interest, these large-scale quantum systems could also serve applications in quantum technologies. Recently, significant progress has been achieved with new theoretical concepts leading to the experimental demonstration of genuine entanglement between up to 2900 atoms (McConnell et al., Nature 2015). Going to larger groups of entangled particles is challenging due to unavoidable noise, decoherence and the lack of robust entanglement witnesses. Here we demonstrate 16 million genuinely entangled atoms in a solid-state quantum memory prepared by the absorption of a single photon. We develop an entanglement witness for quantifying the number of genuinely entangled particles based on the collective effect of directed emission combined with the nonclassical nature of the emitted light. The method is applicable to a wide range of physical systems and is effective even in situations with significant losses. Our results clarify the role of multipartite entanglement in ensemble-based quantum memories as a necessary prerequisite to achieve a high single-photon process fidelity crucial for future quantum networks. On a more fundamental level, our results reveal the robustness of certain classes of multipartite entangled states, contrary to, e.g., Schrödinger-cat states, and that the depth of entanglement can be experimentally certified at unprecedented scales.