Experimental verification of a reversed Clausius inequality in a closed system

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Thermodynamic inequalities characterize the direction of nonequilibrium processes. A prominent example is the Clausius inequality that lower bounds a change in entropy by the ratio of supplied heat and temperature. However, this result presupposes that a system is in contact with a heat bath that drives it to a thermal state. For initially isolated systems that are moved from an equilibrium state by a dissipative heat exchange, the Clausius inequality has been predicted to be reversed. We here experimentally investigate the nonequilibrium thermodynamics of an initially isolated dilute gas of ultracold Cesium atoms that can be either thermalized or pushed out of equilibrium by means of laser cooling techniques. We determine in both cases the phase-space dynamics by tracing the evolution of the gas with position-resolved fluorescence imaging, from which we evaluate all relevant thermodynamic quantities. We confirm the validity of the usual Clausius inequality for the first process and of the reversed Clausius inequality for the second transformation. Our findings provide important insight into thermodynamic inequalities, and the associated direction of nonequilibrium processes, in nanoscopic systems that do not equilibrate on their own.