

# Envisioning a Neutrino Laser

A Bose-Einstein condensate of radioactive atoms could turn into a source of intense, coherent, and directional neutrino beams, according to a theoretical proposal.

By **Kyle G. Leach**

Neutrinos are the most abundant massive particles in the Universe, yet they are the ones about which we know the least. What makes these elusive particles hard to study is their feeble interaction with matter—trillions of neutrinos pass through our bodies every second without leaving a trace. However, neutrinos may hold deep secrets about the Universe—understanding their properties could hint at new particles and forces beyond the standard model of particle physics or shed light on why matter came to dominate over antimatter. Despite these tantalizing prospects, some of the most basic questions about neutrinos remain unanswered. To address such questions experimentally, Benjamin Jones of the University of Texas at Arlington and Joseph Formaggio of MIT suggest that a Bose-Einstein condensate (BEC) of radioactive atoms could offer a platform for building a “neutrino laser” [1]. The scheme would generate an intense, coherent beam of neutrinos that could be a transformative tool for neutrino studies.

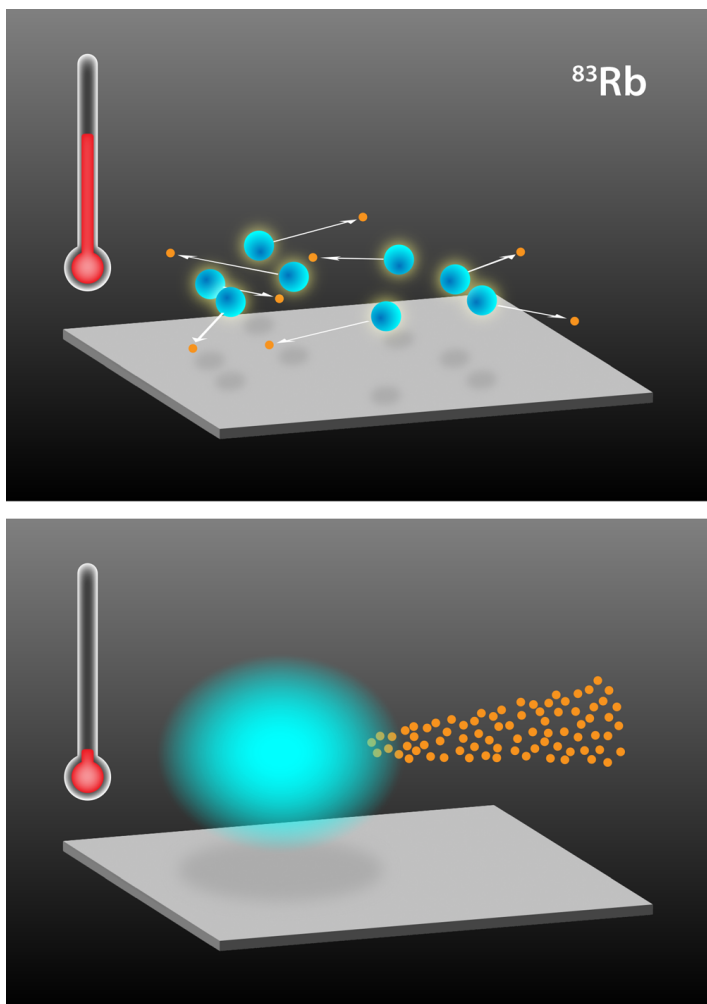
Many neutrino experiments have been carried out at large-scale accelerator facilities, where the neutrinos are produced from high-energy particle collisions. But as the lightest known massive particle (at least a million times lighter than the electron [2]), the neutrino can also be generated and studied in controlled, low-energy settings. Specifically, it can be produced in radioactive-isotope decays and probed through high-precision quantum techniques or through atomic, molecular, and optical (AMO) physics experiments. This field has grown rapidly in recent years, delivering unique experimental results [3–5] and showing intriguing possibilities for future experiments [6]. But finding the right source of neutrinos for these precision techniques has been challenging. Sources based on low-energy neutrinos from radioactive decays lack control over emission time and direction. Furthermore,

practical sources that comply with radiological-safety rules need to work with long-lived radioisotopes, whose rare decays can only generate a scant amount of neutrinos.

A natural concept for producing bright particle beams comes from optics. A laser generates coherent light through stimulated emission, in which one photon triggers the emission of many others at the same energy and in the same direction. Could neutrinos be coaxed into behaving the same way? The analogy quickly fails: Photons are bosons that can share the same quantum state, while neutrinos are fermions that are prevented from doing so by the Pauli principle. And unlike photons, which couple strongly to atoms, neutrinos interact so weakly that stimulated emission is essentially impossible. Jones and Formaggio outline a bold approach to overcoming these barriers based on the phenomenon of superradiance (Fig. 1). While the concept might sound like science fiction, it is rooted in well-established quantum physics.

Superradiance occurs when a group of identical atoms emits radiation collectively, producing a signal much more intense and coherent than the sum of individual atomic emissions. First described by Robert Dicke in 1954 [7], the effect arises when indistinguishable atoms couple to the radiation field, forming a correlated quantum state that decays cooperatively. Superradiance has been extensively demonstrated with photons, and its extension to neutrinos doesn’t face fundamental barriers: The effect doesn’t depend on the statistics of the emitted particles but on that of the emitters. In a BEC, the atoms themselves occupy the same quantum state, making collective neutrino emission possible despite their fermionic nature.

Jones and Formaggio’s superradiance-based idea involves a



**Figure 1:** Top: At high temperature, rubidium atoms decay radioactively through electron capture, releasing neutrinos incoherently. Bottom: At sufficiently low temperatures, the atoms form a Bose-Einstein condensate that could act as a “neutrino laser,” emitting a bright, coherent, directional beam of neutrinos. Credit: APS/Alan Stonebraker

BEC of radioactive rubidium-83 ( $^{83}\text{Rb}$ ) atoms, which decay via nuclear electron capture. In this process, an atom’s inner-shell electron is absorbed by a proton in the nucleus, converting it into a neutron and causing the emission of a neutrino. Generally, such decays occur spontaneously, randomly, and incoherently. But when the  $^{83}\text{Rb}$  atoms are cooled to near absolute zero to form a BEC, they share the same quantum state and become indistinguishable. In this highly correlated state, neutrino emission can occur cooperatively.

For this process to proceed, the indistinguishability of the quantum emitters must be preserved. One factor could spoil this condition: When an atom emits a neutrino, the accompanying nuclear recoil might, in principle, single out the decaying atom from the ensemble and destroy the condensate’s coherence. Jones and Formaggio’s calculations, however, suggest that this potentially detrimental effect should not be impactful. Since all atoms occupy the same quantum state, the neutrino is effectively emitted from the whole condensate, whose coherence is preserved.

Since superradiance scales with the square of the number of correlated atoms, a BEC containing even a modest number of radioisotopes could generate intense pulses of neutrinos with well-defined energy, momentum, and phase—justifying the “neutrino laser” expression. Indeed, the duo’s calculations show that about a million  $^{83}\text{Rb}$  atoms (a billionth of a billionth of a gram of rubidium) could have a dramatic effect. Namely, superradiance would accelerate the isotope’s decay to the point that its half-life would be shortened by nearly a factor of 50,000: from 86.2 days to about 2.5 minutes.

To test their concept, Jones and Formaggio suggest producing  $^{83}\text{Rb}$  BECs and observing the characteristic gamma-ray or x-ray emission from krypton and krypton isomers produced in the  $^{83}\text{Rb}$  decay. An enhancement of these signals due to BEC formation should be observable with state-of-the-art detectors. It’s worth noting that a BEC of radioactive  $^{83}\text{Rb}$  has never been made, but BECs of stable rubidium isotopes ( $^{87}\text{Rb}$ ) are routinely produced. In fact, the first BEC ever demonstrated employed  $^{87}\text{Rb}$  [8]. Jones and Formaggio argue that a  $^{83}\text{Rb}$  condensate could be realized through sympathetic cooling, in which radioactive rubidium atoms are cooled by cotrapped stable rubidium atoms. This approach appears feasible with current cold-atom technology.

An intriguing, albeit highly speculative, possibility comes from the absorption counterpart of superradiance: In principle, collective correlations can enhance not only emission but also absorption rates. Such a BEC might therefore amplify neutrino-capture probabilities, dramatically boosting the efficiency of neutrino detection. This effect would raise tantalizing prospects, such as reaching the sensitivity needed to spot the theorized cosmic neutrino background (CNB)—a relic emission from the first seconds after the big bang. Compared to

the cosmic microwave background, released about 380,000 years later, the CNB would provide a direct probe of a much younger Universe. Jones and Formaggio note, however, that this possibility remains far beyond current experimental reach.

Realizing a neutrino laser will require overcoming several formidable challenges: sustaining a BEC of radioactive  $^{83}\text{Rb}$  against decay losses, ensuring that recoils and other processes do not spoil coherence, and channeling the cooperative emission into a well-defined, directional mode. But the potential payoff is enormous. Beyond enabling precision measurements with neutrinos, one can envision far-future developments ranging from neutrino interferometry to neutrino-based communications.

Combining concepts from nuclear physics, AMO science, and quantum optics, Jones and Formaggio have presented a vision that is both speculative and inspiring. Whether or not a neutrino laser is ever built, the directions inspired by this work will capture the imagination of the neutrino-physics community and beyond.

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