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Superradiant Neutrino Lasers from Radioactive Condensates

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Superradiance emerges from collective spontaneous emission in optically pumped gases, and is characterized by photon emission enhancements of up to $\frac{1}{4}N^2$ in an N atom system. The gain mechanism derives from correlations developed within the decay medium rather than from stimulated emission as in lasing, so an analog of this process should be possible for fermionic final states. We introduce here the concept of superradiant neutrino emission from a radioactive Bose Einstein condensate, which can form the basis for a superradiant neutrino laser. A plausible experimental realization based on a condensate of electron-capture isotope ^{83}Rb could exhibit effective radioactive decay rates accelerated from 86.2 days to minutes in viably sized rubidium condensates of 10^6 atoms.

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The neutrino is a nearly massless particle whose feeble environmental interactions permit coherent quantum mechanical effects. The interferences between neutrino mass states with different de Brogile wavelengths (oscillations) [1], and their modification by refraction in matter [2,3], are prominent and widely studied examples. Within the high neutrino density of supernovae, entanglement through elastic scattering is predicted to lead to collective neutrino oscillations [4]; and the large cross section enhancement associated with coherent elastic neutrino nucleus scattering [5] is a result of in-phase summation of scattering amplitudes from many nucleons.

While some of these coherent phenomena have direct analogies in optics [6], the interference effects available to neutrinos and photons are inequivalent due to the differences between their fermionic and bosonic statistics. One form of coherence that is available to photons but not to neutrinos is lasing. Lasers rely on coherent amplification by stimulated emission (SE), only admissible for bosons. Stimulation of neutrino pairs by photons is possible, and has been invoked as a way to measure the mass of the neutrino [7–11], but direct laser amplification of neutrinos is prohibited because the allowed occupancy of any fermionic mode is limited to zero or one.

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A different coherent amplification effect that has been observed with photons is superradiance (SR) [12]. Originally proposed by Dicke [13], in SR the collective spontaneous emission of $N > 1$ atoms separated by less than one wavelength of light contributes coherently to enhance the radiative decay rates by a factor of up to $\frac{1}{4}N^2$. Following the first observation in optically pumped HF gas [14], SR has also been observed in several other contexts. Unlike in lasing, whereby each photon reinteracts with another atom in a cavity to induce SE, derivations of SR stipulate that "any photon, once produced, escapes from the active volume so fast that it does not have a chance to feed itself back into atomic excitation" [15]. Devices exploiting SR as their primary optical gain mechanism have been realized [6,16], and dubbed "superradiant lasers" (admittedly a misnomer, given the absence of SE in these devices). Reference [17] operates such a device with ≤ 1 photon in the cavity at a time, a strong demonstration that SE is not involved. SR lasers store optical coherence and phase correlations in the gain medium rather than the electromagnetic field, and enhancement occurs through collective spontaneous emission [12,15,16,18–20]. This mechanism does not rely intrinsically on the bosonic nature of light and so should also be admissible for fermions.

In this Letter we discuss the application of SR to produce coherent, amplified neutrino sources. Decays by electron capture (EC) provide a particularly close analogy to the model two-state systems previously invoked in discussions of SR [13,19]. SR β decay also appears to be viable, with cold atomic T being one possible candidate isotope. Finally, the superradiant state also exhibits amplified neutrino interaction rates through enhanced collective neutrino absorption.

One challenge for realizing SR with neutrinos is that the lowest energy detectable neutrinos are produced in β or EC decays with energies of at least a few keV. Ordinary SR requires that the atoms originating each photon (neutrino) should not be distinguishable through measurements that can be made upon that photon (neutrino). This is typically interpreted as a statement that the emitters must be closer together than the DeBrogile wavelength λ. This is one way to achieve such indiscernibility, but there are others. For example, if all initial atoms are prepared in an identical spatial wave function, as in a Bose Einstein Condensate (BEC) [21–23], coherent spontaneous radioactive emission of the daughter particles should also be enabled. This is a proposed method for formation of a gamma ray laser [24], and related forms of collective emission from a BEC have been discussed as mechanisms to achieve implementations based on trapped positronium- [25] gamma-decaying nuclear isomers [26]. Here we investigate the applicability of SR from a BEC to coherently amplified neutrino production.

Enhancement mechanism—The phenomenon of Dicke SR [12] or superfluorescence [20] occurs through the accumulation of quantum correlations between decayed and undecayed atoms in an ensemble. Consider a collection of N identical two-level atoms with upper and lower states labeled $|g_i\rangle$ and $|e_i\rangle$. We can define raising and lowering operators for atom i, as well as the D_i^3 operator,

$$D_i^+ = |e_i\rangle\langle g_i|, \qquad D_i^- = |g_i\rangle\langle e_i|, \tag{1}$$

$$D_i^3 = \frac{1}{2}[|e_i\rangle\langle e_i| - |g_i\rangle\langle g_i|]. \tag{2}$$

The D operators have commutation rules,

$$[D_i^3, D_j^\pm] = \pm\delta_{ij} D_i^\pm, \qquad [D_i^+, D_j^-] = 2\delta_{ij} D_i^3, \tag{3}$$

and the rate of decay to a photon is driven by interaction Hamiltonian H_{int}, which under the rotating wave approximation (RWA) is

$$H_{\mathrm{int,i}} = -i d_a E_l \big(D_i^+ \hat{a}_l + D_i^- \hat{a}_l{}^\dagger\big). \tag{4}$$

E_l is the electric field strength associated with one photon, and $d_a = \langle e|\hat{x}|g\rangle$ is the dipole matrix element that controls the rate of optical transitions. In a sufficiently optically pumped gas we can consider the initial state to be fully excited, $|\psi(0)\rangle = |e_1 e_2 \ldots e_N\rangle$. Despite all atoms being in $|e\rangle$ we emphasize that this is *not* a BEC, since we are labeling only the excitation level of each atom; each also possesses a position-space wave function, which for traditional SR can be assumed to be distinct and nonoverlapping.

The simplest SR condition is that all atoms are motionless and contained in a small volume compared to the transition wavelength $\lambda = hc/(E_e - E_g)$. In this case we can express the full interaction Hamiltonian as

$$H_{\mathrm{int}} = \sum_i H_{\mathrm{int},i} = -i d_a E_l \big(D^+ \hat{a}_l + D^- \hat{a}_l{}^\dagger\big), \tag{5}$$

where we have identified the "D spin" of the entire system $D \equiv \sum_i D_i$. The eigenstates of D are constructed by analogy to coupling many spin-1/2 angular momenta. The largest J-plet is comprised of N states with quantum number M ranging between $\pm\frac{1}{2}N$, obtained via the lowering operation on $|\psi(0)\rangle$

$$|JM\rangle = \sqrt{\frac{(J+M)!}{N!(J-M)!}}(D^-)^{J-M}|eeee\ldots e\rangle. \tag{6}$$

The $|JM\rangle$ state has $J+M$ atoms in $|e\rangle$ and $J-M$ atoms in $|g\rangle$, appropriately symmetrized. Photon emission is generated by the D^- in H_{int}, so each emission ladders downward between elements of the same J-multiplet. The rate of emission W_N is found via Fermi's golden rule,

$$W_N \propto |\langle J, M-1|H_{\mathrm{int}}|J, M\rangle|^2. \tag{7}$$

Only one final state has a nonzero amplitude given this initial one, so Eq. (7) can be written as

$$W_N = \sum_f \langle JM|D^+\hat{a}|f\rangle\langle f|D^-\hat{a}^\dagger|JM\rangle\Gamma_\gamma \tag{8}$$

$$= \langle D^+D^-(1+\hat{a}^\dagger\hat{a})\rangle\Gamma_\gamma, \tag{9}$$

where Γ_γ is the single particle rate, $[\hat{a}, \hat{a}^\dagger] = 1$ has been employed to move $\hat{a}$ to the right, and the expectation $\langle\rangle$ is implicitly taken for the initial state only. For emission into a cavity that already contains n photons we find a decay rate enhanced by $1+n$,

$$W_N = (1+n)\langle D^+D^-\rangle\Gamma_\gamma, \tag{10}$$

demonstrating conventional lasing through SE. When $n = 0$ photons are present the rate is instead

$$W_N = \langle D^+D^-\rangle\Gamma_\gamma \tag{11}$$

$$= (J+M)(J-M+1)\Gamma_\gamma. \tag{12}$$

W_N increases from $N\Gamma_\gamma$ when $M = J = \frac{1}{2}N$ (nothing has decayed), to $\frac{1}{2}N(\frac{1}{2}N+1)\Gamma_\gamma$ when $M = 0$ (half of the atoms have decayed). For large N, a dramatic enhancement for the partially decayed state beyond the ordinary fluorescence rate $(J+M)\Gamma_\gamma$ is observed, embodying SR amplification.

Consider now the analogous system involving a BEC that undergoes EC to produce neutrinos. The two atomic basis states are a parent $|p_i\rangle$ and a daughter emitted alongside a neutrino $|d_i\rangle$. For both β decay and EC, the analogous operators to $D^\pm$ are isospin ladders $\tau^\pm$. The total interaction Hamiltonian can be written, this time without requiring the RWA, as

$$H_{\text{int}}^{\nu} = \sum_i \left(\tau_i^+ \hat{a}_\nu + \tau_i^- \hat{a}_\nu^\dagger\right). \tag{13}$$

In a BEC all neutrinos necessarily emerge from indistinguishable atomic states, so we no longer require the long wavelength assumption. Equivalent arguments are then used to obtain the total emission rate W_N^ν,

$$W_N^\nu = \langle \mathcal{T}^+ \mathcal{T}^- (1 - \hat{a}_\nu^\dagger \hat{a}_\nu) \rangle \Gamma_\nu, \tag{14}$$

now in terms of $\mathcal{T} = \sum_i \tau_i$ and applying fermionic commutation relations $\{\hat{a}_\nu, \hat{a}_\nu^\dagger\} = 1$.

Once again we distinguish between the cases where there is or is not a neutrino in the emission region at the time of decay. With a neutrino present, $\hat{a}_\nu^\dagger \hat{a}_\nu |i\rangle = |i\rangle$ and so $W_N^\nu = 0$: Pauli blocking inhibits the lasing effect that was observable with photons. On the other hand, if each neutrino quickly leaves then $\hat{a}_\nu^\dagger \hat{a}_\nu |i\rangle = 0$, again yielding

$$W_N^\nu = (J + M)(J - M + 1)\Gamma_\nu. \tag{15}$$

Thus SR emission is expected for a radioactive BEC decaying to neutrinos.

The quantum correlations leading to SR accumulate within the gain medium during decay. In the BEC example, the decay daughters are likely to escape and interact with the environment on timescales faster than this accumulation occurs. We must therefore examine whether such interactions destroy a coherent amplification process. To this end, we consider the process again incorporating both the state label ($|e\rangle$ vs $|g\rangle$ or $|p\rangle$ vs $|d\rangle$) and also the position wave function of each atom $|\phi_i\rangle$. Under the original Dicke mechanism, the ϕ_i are distinguishable and nonoverlapping.

Considering a three-atom system for illustration, the undecayed state $|\psi_0\rangle$ decays to produce the first photon as $|\psi_0\rangle \to |\psi_0'\rangle$ with rate $W_{N=3}^{1\gamma}$,

$$|\psi_0\rangle = \left|\frac{3}{2}, \frac{3}{2}\right\rangle = |e_1 e_2 e_3\rangle \otimes |\phi_1^e \phi_2^e \phi_3^e\rangle \tag{16}$$

$$\to |\psi_0'\rangle = (|e_1 e_2 g_3\rangle \otimes |\phi_1^e \phi_2^e \phi_3^g\rangle + \{\ldots\}) \otimes |\gamma\rangle, \tag{17}$$

$$W_{N=3}^{1\gamma} = \sum_\lambda |\langle \lambda | \psi_1 \rangle|^2 \Gamma_\gamma = 3\Gamma_\gamma. \tag{18}$$

The $\{\ldots\}$ here denotes summation over permutations of 1,2,3, and $\sum_\lambda$ implies both summation over flavor and integration over position bases. For the first decay $W_N = N\Gamma$ so there is no SR enhancement, as expected. More interesting is the second decay, which occurs from a Dicke state,

$$|\psi_1\rangle = \frac{|e_1 e_2 g_3\rangle \otimes |\phi_1^e \phi_2^e \phi_3^g\rangle + \{\ldots\}}{\sqrt{3}} \tag{19}$$

$$\to |\psi_1'\rangle = \frac{|g_1 e_2 g_3\rangle \otimes |\phi_1^g \phi_2^e \phi_3^g\rangle + \{\ldots\}}{\sqrt{3}} \otimes |\gamma\rangle, \tag{20}$$

$$W_{N=3}^{2\gamma} = \sum_\lambda |\langle \lambda | \psi \rangle|^2 \Gamma_\gamma = 4\Gamma_\gamma. \tag{21}$$

Only two $|e\rangle$ are present, yet the decay rate scales as $4\Gamma_\gamma$ due to SR. The origin of the enhancement is that, for example, the $|g_1 e_2 g_3\rangle$ in $|\psi_1'\rangle$ is generated indistinguishably from both the $|e_1 e_2 g_3\rangle$ and $|g_1 e_2 e_3\rangle$ terms in $|\psi_1\rangle$, which add coherently. This interpretation is further developed in [27], which also explores the effects of relaxing the long-wavelength approximation.

Decohering interactions can be included in this model via a von Neumann measurement, in which the environment prepared in initial state $|\epsilon_0\rangle$ becomes entangled with one of the daughter particles i via

$$|\phi_i^g\rangle \otimes |\epsilon_0\rangle \to |\phi_i'\rangle \otimes |\epsilon_i\rangle, \tag{22}$$

and then with another atom j, as

$$|\phi_i'\rangle \otimes |\phi_j^g\rangle \otimes |\epsilon_i\rangle \to |\phi_i'\rangle \otimes |\phi_j'\rangle \otimes |\epsilon_{ij}\rangle. \tag{23}$$

We assume that the environment is not so altered by i that $|\phi_j'\rangle$ depends strongly on whether j or i was emitted first, but that the final state of environment is nevertheless distinct for the two orderings, $|\epsilon_{ij}\rangle \neq |\epsilon_{ji}\rangle$. Under these assumptions a modified decay rate is derived,

$$\tilde{W}_{N=3}^{2\gamma} = \frac{2}{3}\left(3 + \sum_{i<j} \mathcal{R}\langle \epsilon_{ij} | \epsilon_{ji} \rangle\right)\Gamma_\gamma. \tag{24}$$

As is typical in decoherence models, Eq. (24) has a coherent limit when the environment contains no distinguishing information about the emission order, $\langle \epsilon_{ij} | \epsilon_{ji} \rangle = 1$ and $W_{N=3}^{2\gamma} = 4\Gamma_\gamma$, and an incoherent one when the different entangled environment states are completely distinguishable, $\langle \epsilon_{ij} | \epsilon_{ji} \rangle = \delta_{ij}$ and $W_{N=3}^{2\gamma} = 2\Gamma_\gamma$. These limits correspond to superradiant emission and ordinary fluorescence, respectively.

For neutrino emission from a radioactive BEC, the spatial wave functions are necessarily all identical, $|\phi_i^p\rangle = |\phi^p\rangle$, and $|\phi_i^d\rangle = |\phi^d\rangle$. As a result, environmental interactions of the daughters all take the same form:

$$|\phi^d\rangle \otimes |\epsilon_0\rangle \to |\phi'\rangle \otimes |\epsilon\rangle, \tag{25}$$

where in this case $|\epsilon\rangle$ has no dependence on i at all. Since the environment state now carries no subscripts, coherent amplification is always maintained,

$$\tilde{W}^{2\nu}_{N=3} = 4\Gamma_\nu. \tag{26}$$

It is remarkable that for emission from the fully spatially degenerate initial state provided by a BEC, coherence appears possible even in the presence of MeV-scale momentum transfers associated with the recoiling daughter atoms. This is so because even though the recoil can transfer information about its origin to the surroundings, it remains impossible to ascertain which parent atom has decayed. Furthermore, since it is the rate of neutrino-daughter pairs that is amplified, the entanglement between the neutrinos and the recoils also does not suppress coherence. Rather, the correlations among trapped parent atoms within the decaying condensate are sufficient to preserve SR enhancement.

Amplified ν emission—To realize this effect experimentally, we require an isotope that (1) is radioactive; (2) has a bosonic neutral atom; (3) has such a sufficiently short half-life that reaching a ~50% population is viable during a trappable lifetime; (4) is practically coolable to degeneracy, ideally with laser cooling; and (5) offers a method for monitoring the decay rate.

Several candidates in the table of nuclides meet these criteria, one example being ^{83}Rb. The neutral atom contains 46 neutrons, 37 protons, and 37 electrons, meaning it is a boson and can be condensed. It decays via EC to ^{83m}Kr, which can be counted by subsequent decay x-rays produced by deexcitation of the decay daughter with a half-life of 1.83 hours. ^{83}Rb has a half-life of $\tau_{1/2} = 86.2$ days, which is long enough for convenient handling but short enough for depletion to be measured on viable timescales.

Other isotopes of Rb are frequently laser cooled to produce BEC, with works such as Ref. [28] producing ^{87}Rb condensates with 2×10^6 atoms at a 16 s repetition rate. As in most studies of rubidium BECs, Ref. [28] employs adiabatic cooling, using a 49 μK magnetic trap loaded through a sequence of optical precooling methods. This leads to a final condensate temperature of of 0.32 μK, comfortably below the critical temperature of $T_c = 0.5$ μK. Condensates of ^{85}Rb have also been produced [29]. There, polarization gradient cooling in a 3D optical lattice and a compressible double-crossed dipole trap were employed, in order to circumvent difficulties associated with the more difficult collisional properties of ^{85}Rb relative to ^{87}Rb. Condensates of $N \sim 2 \times 10^5$ ^{85}Rb atoms were realized, on a few-second timescale. No condensates of ^{83}Rb have been reported to date, though its collisional properties have been presented in Ref. [30] as being remarkably similar to those of ^{87}Rb. Reference [30] also discusses the possible production of a double condensate of ^{87}Rb and ^{83}Rb, enabled through a convenient and tunable Feshbach resonance. In such a system the nonradioactive ^{87}Rb would serve as a passive background species and not be expected to interfere with the emission phenomena, and so this mixture could also serve as a convenient SR neutrino laser gain medium as an alternative to an ensemble of pure ^{83}Rb.

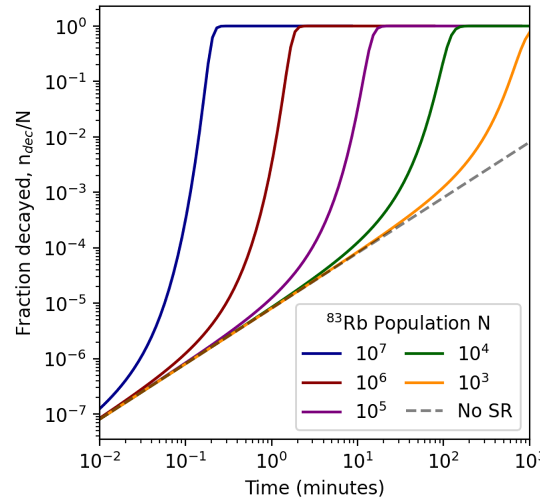

FIG. 1. Comparison of the SR and ordinary fluorescence decay rates in ^{86}Rb.

Assuming a suitable BEC can be produced, the effects of SR enhancement become apparent quickly. The number of decayed atoms n_{dec} exhibits exponential growth,

$$n_{\mathrm{dec}}(t) = N \frac{e^{(N+1)\Gamma_\nu t} - 1}{e^{(N+1)\Gamma_\nu t} + N}. \tag{27}$$

We quantify the gain associated with the SR process by constructing an equivalent "half-life" ($\tilde{\tau}_{1/2}$). In the limit that $N \gg 1$, we find that

$$\frac{\tilde{\tau}_{1/2}}{\tau_{1/2}} \simeq \frac{\ln(N)}{(N+1)\ln(2)}. \tag{28}$$

For ^{83}Rb the accelerated half-life drops to $\tilde{\tau}_{1/2} \simeq 148$ s with a BEC of 10^6 atoms. Figure 1 shows the population evolution under the SR mechanism (solid lines) in comparison to the ordinary radioactive decay (dashed) for various condensate sizes, illustrating this large enhancement.

Amplified ν capture—Discussion of amplified decay rates invites consideration of amplified neutrino capture on the SR state. Aspects of this problem have recently been discussed by others, in the context of axion, dark matter, and reactor neutrino searches [31]. This could have various applications, including detection of the relic neutrino density from the primordial big bang. Tritium (T) is one isotope commonly targeted for relic neutrino capture searches, via $\nu_e + {}^3\mathrm{H} \to e^- + {}^3\mathrm{He}$, and cooling of T is an active ongoing effort for direct neutrino mass searches [32]. The rate of neutrino capture on T is determined by the overlap of the BEC and neutrino spatial wave functions, and is directly related to the β decay rate. Cocco *et al.* [33] provide an estimate of connecting the half-life of beta decay to neutrino capture,

$$\lambda_\nu \simeq \int \frac{G_F^2}{\pi} \frac{p_e E_e F(Z, E_e)}{\exp(p_\nu/T_\nu)+1} \frac{d^3 p_\nu}{(2\pi)^3} \tag{29}$$

$$\simeq 0.66 \times 10^{-23} \Gamma_\beta, \tag{30}$$

where Γ_β is the tritium beta decay rate (2×10^{-9} s^{-1}).

The SR mechanism does give an enhancement to this process which is analogous to the enhancement provided for emission from the Dicke state. Even with SR, between 10^{20} and 10^{25} atoms must be held for timescales exceeding one year in order to detect a few relic neutrino events. This is mainly because one needs to initiate the decay of a few events before the enhancement process can start to take hold. As such, while the SR mechanism indeed appears to have implications for accelerated neutrino capture, it does not appear to offer obvious sensitivity to the cosmological relic neutrino background.

Conclusion—We have introduced the concept of a superradiant source for enhanced neutrino emission via collective spontaneous decay of a radioactive BEC. The isotope ^{83}Rb is presented as a promising candidate, with an 86 day half-life that may be accelerated to minutes by superradiance.

Many aspects are absent from our discussion. These include a detailed presentation of a method for cooling the radioactive vapor to degeneracy, management of condensate heating by escaping particles and their energy losses into the trap, the method of decay rate measurement, and others. We defer such practical considerations to future work. Our primary conclusion is that there is a mechanism by which a coherent, enhanced, "laserlike" emission of neutrinos is possible, and that it is potentially experimentally observable. The enhancement factor is controllable via the size of the condensate population, and increases of order 10^6 are accessible with reasonably sized, radioactive Bose Einstein condensates.

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Data availability—The data that support the findings of this Letter are openly available [34].

[1] Carlo Giunti and Chung W. Kim, *Fundamentals of Neutrino Physics and Astrophysics* (Oxford University Press, New York, 2007).
[2] Tzee-Ke Kuo and James Pantaleone, Neutrino oscillations in matter, Rev. Mod. Phys. **61**, 937 (1989).
[3] S. P. Mikheyev and A. Yu. Smirnov, Resonant neutrino oscillations in matter, Prog. Part. Nucl. Phys. **23**, 41 (1989).
[4] Huaiyu Duan, George M. Fuller, and Yong-Zhong Qian, Collective neutrino oscillations, Annu. Rev. Nucl. Part. Sci. **60**, 569 (2010).
[5] D. Akimov, J. B. Albert, P. An, C. Awe, P. S. Barbeau, B. Becker, V. Belov, A. Brown, A. Bolozdynya, B. Cabrera-Palmer *et al.*, Observation of coherent elastic neutrino-nucleus scattering, Science **357**, 1123 (2017).
[6] J. M. Weiner, K. C. Cox, J. G. Bohnet, and J. K. Thompson, Phase synchronization inside a superradiant laser, Phys. Rev. A **95**, 033808 (2017).
[7] N. Song, R. Boyero Garcia, J. J. Gomez-Cadenas, M. C. Gonzalez-Garcia, A. Peralta Conde, and J. Taron, Conditions for statistical determination of the neutrino mass spectrum in radiative emission of neutrino pairs in atoms, Phys. Rev. D **93**, 013020 (2016).
[8] Jue Zhang and Shun Zhou, Improved statistical determination of absolute neutrino masses via radiative emission of neutrino pairs from atoms, Phys. Rev. D **93**, 113020 (2016).
[9] M. Yoshimura and N. Sasao, Radiative emission of neutrino pair from nucleus and inner core electrons in heavy atoms, Phys. Rev. D **89**, 053013 (2014).
[10] M. Yoshimura, Neutrino pair emission from excited atoms, Phys. Rev. D **75**, 113007 (2007).
[11] Shao-Feng Ge and Pedro Pasquini, Unique probe of neutrino electromagnetic moments with radiative pair emission, Phys. Lett. B **841**, 137911 (2023).
[12] Nicholas E. Rehler and Joseph H. Eberly, Superradiance, Phys. Rev. A **3**, 1735 (1971).
[13] Robert H. Dicke, Coherence in spontaneous radiation processes, Phys. Rev. **93**, 99 (1954).
[14] N. Skribanowitz, I. P. Herman, J. C. MacGillivray, and M. S. Feld, Observation of Dicke superradiance in optically pumped HF gas, Phys. Rev. Lett. **30**, 309 (1973).
[15] R. Bonifacio, P. Schwendimann, and Fritz Haake, Quantum statistical theory of superradiance. I, Phys. Rev. A **4**, 302 (1971).
[16] F. Haake, M. I. Kolobov, C. Fabre, E. Giacobino, and S. Reynaud, Superradiant laser, Phys. Rev. Lett. **71**, 995 (1993).
[17] Justin G. Bohnet, Zilong Chen, Joshua M. Weiner, Dominic Meiser, Murray J. Holland, and James K. Thompson, A steady-state superradiant laser with less than one intracavity photon, Nature (London) **484**, 78 (2012).
[18] E. Akkermans, A. Gero, and R. Kaiser, Photon localization and Dicke superradiance in atomic gases, Phys. Rev. Lett. **101**, 103602 (2008).
[19] Michel Gross and Serge Haroche, Superradiance: An essay on the theory of collective spontaneous emission, Phys. Rep. **93**, 301 (1982).
[20] M. F. H. Schuurmans, Q. H. F. Vrehen, D. Polder, and H. M. Gibbs, Superfluorescence, in *Advances in Atomic and Molecular Physics* (Elsevier, New York, 1982), Vol. 17, pp. 167–228.
[21] Allan Griffin, David W. Snoke, and Sandro Stringari, *Bose-Einstein Condensation* (Cambridge University Press, Cambridge, England, 1996).
[22] Christopher J. Pethick and Henrik Smith, *Bose–Einstein Condensation in Dilute Gases* (Cambridge University Press, Cambridge, England, 2008).

[23] Dominik Schneble, Yoshio Torii, Micah Boyd, Erik W. Streed, David E. Pritchard, and Wolfgang Ketterle, The onset of matter-wave amplification in a superradiant Bose-Einstein condensate, Science **300**, 475 (2003).

[24] H. K. Avetissian, A. K. Avetissian, and G. F. Mkrtchian, Self-amplified gamma-ray laser on positronium atoms from a Bose-Einstein condensate, Phys. Rev. Lett. **113**, 023904 (2014).

[25] H. K. Avetissian, A. K. Avetissian, and G. F. Mkrtchian, Gamma-ray laser based on the collective decay of positronium atoms in a Bose-Einstein condensate, Phys. Rev. A **92**, 023820 (2015).

[26] Luca Marmugi, Philip M. Walker, and Ferruccio Renzoni, Coherent gamma photon generation in a Bose–Einstein condensate of ^{135m}Cs, Phys. Lett. B **777**, 281 (2018).

[27] R. Wiegner, J. Von Zanthier, and Girish S. Agarwal, Quantum-interference-initiated superradiant and subradiant emission from entangled atoms, Phys. Rev. A **84**, 023805 (2011).

[28] Y.-J. Lin, Abigail R. Perry, Robert L. Compton, Ian B. Spielman, and James V. Porto, Rapid production of ^{87}Rb Bose-Einstein condensates in a combined magnetic and optical potential, Phys. Rev. A **79**, 063631 (2009).

[29] H. Otoishi, S. Nagata, T. Yukawa, K. Yamashita, and T. Kinoshita, Rapid production of a ^{85}Rb Bose-Einstein condensate in a double compressible optical dipole trap, Phys. Rev. A **102**, 023316 (2020).

[30] J. P. Burke, Jr and J. L. Bohn, Ultracold scattering properties of the short-lived Rb isotopes, Phys. Rev. A **59**, 1303 (1999).

[31] Asimina Arvanitaki, Savas Dimopoulos, and Marios Galanis, Superradiant interactions of the cosmic neutrino background, axions, dark matter, and reactor neutrinos, Phys. Rev. D **111**, 055015 (2025).

[32] A. Ashtari Esfahani, S. Böser, N. Buzinsky, M. C. Carmona-Benitez, C. Claessens, L. De Viveiros, P. J. Doe, S. Enomoto, M. Fertl, J. A. Formaggio *et al.*, The project 8 neutrino mass experiment, arXiv:2203.07349.

[33] A. G. Cocco, G. Mangano, and M. Messina, Probing low energy neutrino backgrounds with neutrino capture on beta decaying nuclei, J. Phys. Conf. Ser. **110**, 082014 (2008).

[34] 10.5281/zenodo.15858627