Time-Resolved and Superradiantly Amplified Unruh Effect

Akhil Deswal,[1,*] Navdeep Arya,[2,†] Kinjalk Lochan,[1] and Sandeep K. Goyal[1]

[1]*Department of Physical Sciences, Indian Institute of Science Education and Research (IISER) Mohali, Sector 81 SAS Nagar, Manauli PO 140306, Punjab, India*

[2]*Department of Physics, Stockholm University, Roslagstullsbacken 21, 106 91 Stockholm, Sweden*

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We identify low-acceleration conditions under which the Unruh effect manifests as an early superradiant burst in a collection of excited atoms. The resulting amplified Unruh signal is resolved from the inertial signal both in time and intensity. We demonstrate theoretically that these conditions are realized inside a subresonant cavity that highly suppresses the response of an inertial atom, while allowing significant response from an accelerated atom as, owing to the acceleration-induced spectral broadening, it can still couple to the available field modes. The setup thus selectively amplifies the modified field fluctuations underlying the Unruh effect into an early superradiant burst. In comparison, the field fluctuations perceived inertially would cause a superradiant burst much later. In this way, we simultaneously address the extreme acceleration requirement, the weak Unruh signal, and the dominance of the inertial signal, all within a single experimental arrangement.

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Introduction—The quantum field fluctuations are known to be altered under various conditions, leading to phenomena like the Casimir effect [1], the Schwinger effect [2], Hawking radiation [3], and particle creation in an expanding universe [4]. Additionally, the concepts of vacuum and particle content of a quantum field are inherently observer dependent, as elegantly encapsulated in the Fulling-Davies-Unruh effect [5–8]—predicting that a uniformly accelerated observer perceives the inertial vacuum of a free quantum field to be in a thermal state at a temperature T_{U} proportional to its acceleration $a: T_{\mathrm{U}} = \hbar a/2\pi k_{\mathrm{B}} c$.

While individual atoms provide valuable insights into such phenomena, a collection of atoms can function as an even more sophisticated probe [9], leveraging the rich dynamics of collective effects [10,11]. For instance, photon emission from an extended sample of N excited atoms sensitively depends on the distribution of atoms in the sample and the properties of the electromagnetic field to which the atoms are coupled [12–15]. Although a single excited atom decays spontaneously with an exponential profile at an emission rate γ, the collective behavior of a group of atoms can significantly modify the emission process [10]. In an array of excited atoms where the atoms are indistinguishable with respect to their coupling to the electromagnetic field, correlations begin to develop between them as soon as any atom in the array undergoes spontaneous emission [11]. The correlations build up during a time period $0 < \tau < \tau_{\mathrm{d}}$, ultimately leading to an intense event of photon emission, known as the superradiant burst, at the *superradiant delay time* τ_{d}. The delay time is thus sensitive to the field fluctuations experienced by the atomic sample, and therefore should respond to, for example, the sample's acceleration or the presence of a gravitational field [9]. The intense photon emission rate lasts for a short period τ_{sr}, known as the superradiance time. The superradiance process features a maximum emission rate scaling super-linearly with the total number of participating atoms, well-defined directionality, and a time-resolving nature characterized by the superradiant delay time τ_{d} and the superradiance time τ_{sr} [10,11].

The Unruh effect, of great interest partly due to its close connection to the Hawking effect [16], remains untested due to the requirement of extreme accelerations. At achievable accelerations, the expected signal, being extremely weak, is easily overwhelmed by the inertial noise and the noise due to ambient laboratory temperature. In this Letter, we leverage the acceleration-induced nonresonant behavior of an atom, inside a subresonant cavity, in combination with the hallmarks of superradiance to obtain a time-resolved and highly amplified Unruh signal at low accelerations. Refer to Fig. 1 for a graphical summary of the results.

*Contact author: akhildeswal.phy@gmail.com

†Contact author: navdeep.arya@fysik.su.se, navdeeparya.me@gmail.com

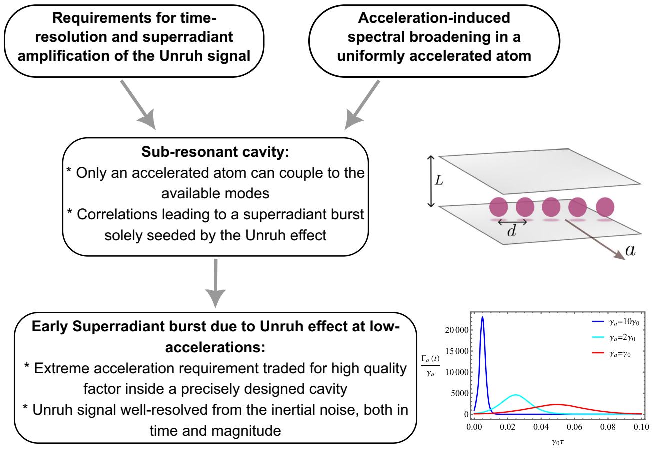

FIG. 1. Graphical summary of the results.

Collective response of atoms—Consider N identical two-level atoms forming a one-dimensional ordered array with interatomic spacing $\hat{y}d$, transverse to their motion along $\hat{z}$ direction. The atoms are coupled to an electromagnetic field between two parallel mirrors with separation $\hat{x}L$ and reflectivity R. Each atom has a transition frequency ω_0 and the corresponding transition wavelength is denoted by λ_0. We address an array subjected to uniform linear acceleration, in which each atom takes the trajectory $t(\tau) = a^{-1}\sinh(a\tau), z(\tau) = a^{-1}\cosh(a\tau)$, as a Rindler array. Here, τ is the proper time of an atom. The total photon emission rate of such an array is obtained as (see Supplemental Material [17] for details)

$$\Gamma_\mathrm{a}(\tau) = \frac{\gamma_\mathrm{a}}{4\mu_\mathrm{a}}(\mu_\mathrm{a}N + 1)^2\ \mathrm{sech}^2\left(\frac{\tau - \tau_\mathrm{d}}{2\tau_\mathrm{sr}}\right), \tag{1}$$

where γ_a is the emission rate of a single Rindler atom, $\tau_\mathrm{d} \equiv \ln(\mu_\mathrm{a}N)/\gamma_\mathrm{a}(\mu_\mathrm{a}N + 1)$ is the superradiant delay time, and $\tau_\mathrm{sr} \equiv 1/\gamma_\mathrm{a}(\mu_\mathrm{a}N + 1)$ is the superradiance time as marked in Fig. 3(c). The *shape factor* μ_a of the array is defined as $\mu_\mathrm{a} \equiv \gamma_\mathrm{a}^{-1}N^{-2}\sum_{i\neq j}\gamma_{ij}^{(\mathrm{a})}$, where $\gamma_{ii}^{(\mathrm{a})} = \gamma_\mathrm{a}$ and for $i \neq j$, $\gamma_{ij}^{(\mathrm{a})}$ quantifies the extent to which i th and j th atoms in the array influence each other's dynamics. The shape factor depends on the distribution of atoms in the sample and the properties, like mode structure and particle content, of the field to which the atoms are coupled. In addition, it is sensitive to the acceleration of the array and the presence of any gravitational effects [9].

Condition for time-resolution and superradiant enhancement of the Unruh signal—An intuitive way to appreciate the shape factor is to think of μN as the *effective number of cooperating atoms* [13]. In the small sample limit, the so-called Dicke regime [10], $\mu N \to N - 1$, meaning that all the atoms in the sample cooperate, that is, the cooperative effects are the strongest. In general, under the effect of uniform acceleration, $\gamma_\mathrm{a}/\gamma_0$ increases while μ_a/μ_0 decreases as a function of acceleration [see Fig. 3(b)]. We are interested in resolving the superradiant burst of a Rindler array from that of an inertial array. The occurrence of the two superradiant peaks will differ if the corresponding superradiant delay times are different enough. Further, the overlap of the two superradiant temporal profiles can be reduced if the collective effects are not compromised much due to the acceleration—this ensures that τ_sr, the time period over which superradiance occurs, remains small.

To this end, consider the ratio of the superradiant delay times for a Rindler and an inertial array:

$$\frac{\tau_\mathrm{d}^{(\mathrm{a})}}{\tau_\mathrm{d}^{(0)}} = \frac{\gamma_0(\mu_0N + 1)\ln(\mu_\mathrm{a}N)}{\gamma_\mathrm{a}(\mu_\mathrm{a}N + 1)\ln(\mu_0N)}. \tag{2}$$

The two signals are well resolved in time if $\tau_\mathrm{d}^{(\mathrm{a})} < \tau_\mathrm{d}^{(0)}$. If we chose d/λ_0 such that both $\mu_\mathrm{a}N$ and μ_0N are much greater than 1 (ensuring strong collective effects), the requirement simplifies to

$$\frac{\tau_\mathrm{d}^{(\mathrm{a})}}{\tau_\mathrm{d}^{(0)}} \approx \frac{\gamma_0\mu_0N}{\gamma_\mathrm{a}\mu_\mathrm{a}N}\frac{\ln(\mu_\mathrm{a}N)}{\ln(\mu_0N)} < 1.$$

At the same time, since the maximum superradiant emission rate scales as $(\mu N)^2$, if we want time resolution of the two signals without compromising on superradiant amplification of the noninertial signal, we additionally require $\mu_\mathrm{a}/\mu_0 \approx 1$ (with μ_a and μ_0 each individually close to unity). Thus, the requirements to *time resolve and superradiantly amplify* the Unruh signal are $\gamma_\mathrm{a}/\gamma_0 \gg 1$ and $\mu_\mathrm{a}/\mu_0 \approx 1$. Under these conditions, the correlations between atoms that eventually lead to a superradiant burst build much faster in a Rindler array, with the buildup exclusively driven by the Unruh effect. The superradiant burst would thus be solely seeded by the modified field fluctuations underlying the Unruh effect predicted to be experienced by an accelerated system. This early superradiant burst would serve as a clear signature of the Unruh effect. It is noteworthy that the inertial vacuum state restricted to either the left or right Rindler wedge is in fact a thermal state at temperature T_U in the kind of cavity setup under consideration here—that is, where the cavity modifies the density of field modes only in the direction transverse to the observer's acceleration [29]. Since $\tau_\mathrm{d}^{(\mathrm{a})}/\tau_\mathrm{d}^{(0)} \approx \gamma_0/\gamma_\mathrm{a}$ under the conditions stated above, delay-time measurements in a setup first benchmarked with an inertial sample of atoms [i.e., γ_0, μ_0, and $t_\mathrm{d}^{(0)}$ determined] can be used to obtain γ_a. These values can then be verified against the theoretical prediction for γ_a. Consequent upon this verification, one may infer the corresponding Unruh temperature directly from the expression $T_\mathrm{U} = \hbar a/2\pi k_\mathrm{B}c$.

To understand the effect of acceleration on μ, in Fig. 3(b) we analyze the behavior of $\gamma_{ij}^{(\mathrm{a})}/\gamma_\mathrm{a}$ as a function of d/λ_0 for different accelerations. Note that for a larger acceleration

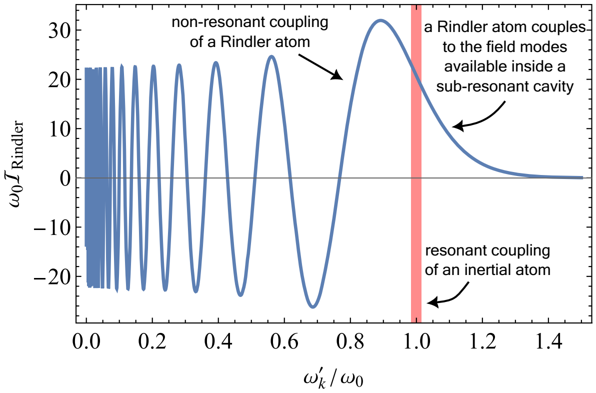

FIG. 2. Acceleration-induced spectral broadening in a Rindler atom. $\mathcal{I}_{\mathrm{Rindler}}$ is the spectral response of a uniformly accelerated atom. The red band shows an inertial atom's resonant coupling, i.e., to modes with $\omega'_k \approx \omega_0$. The blue curve shows nonresonant coupling of a Rindler atom to field modes. The plot is for $a/\omega_0 = 10^{-1}$.

($a/\omega_0 \sim 10^{-5}$), the cooperation between i th and j th atoms reduces quicker with increasing d/λ_0. On the other hand, for a smaller acceleration ($a/\omega_0 \sim 10^{-7}$), the cooperation is almost the same as for the inertial case over the range of d/λ_0 shown. Therefore, the larger the acceleration, quicker is the fall in $\gamma_{ij}^{(\mathrm{a})}/\gamma_{\mathrm{a}}$ with increasing d/λ_0. Importantly, a finite, yet small, interatomic distance is required to preserve collective effects against dephasing due to coherent dipole-dipole interactions [11]. This effect in our setup is analyzed in Supplemental Material [17]. Therefore, the requirement of $\mu_{\mathrm{a}}/\mu_0 \approx 1$ can be comfortably fulfilled at lower accelerations.

Further, note that in general the emission rate γ_{a} of an accelerated atom can be written as $\gamma_{\mathrm{a}} = \gamma_0 + \tilde{\gamma}(\alpha)$, $\alpha \equiv a/\omega_0$, where the last contribution is purely noninertial, that is, $\lim_{\alpha\to 0}\tilde{\gamma}(\alpha) = 0$. As we have already noted that $\mu_{\mathrm{a}}/\mu_0 \approx 1$ can be achieved at low accelerations, clearly, the time-resolution and superradiant enhancement of the Unruh signal hinges on achieving $\gamma_{\mathrm{a}}/\gamma_0 \gg 1$. For $\gamma_{\mathrm{a}}/\gamma_0 = 1 + \tilde{\gamma}/\gamma_0$ to be much greater than unity, we require $\tilde{\gamma}/\gamma_0 \gg 1$, which could not be achieved in any of the proposals for observing the Unruh effect so far.

Next, we demonstrate that $\tilde{\gamma}(\alpha)/\gamma_0 \gg 1$ can be achieved inside a subresonant cavity by optimally harnessing the acceleration-induced nonresonant behavior of a Rindler atom.

Acceleration-induced spectral broadening—The acceleration induces a nonresonant behavior in an atom, broadening its spectrum. In Fig. 2, we show the field modes that participate in the response of a Rindler atom, where $\omega_0\mathcal{I}_{\mathrm{Rindler}}$ is the strength of participation of a given mode (see Supplemental Material [17] for more details). Note some intriguing features in a Rindler atom's coupling to the field modes: for mode frequencies $\omega'_k < \omega_0$, the atom couples constructively ($\mathcal{I}_{\mathrm{Rindler}} > 0$) to some field modes and destructively ($\mathcal{I}_{\mathrm{Rindler}} < 0$) to others. More importantly, it couples (constructively) to modes having $\omega'_k > \omega_0$, a feature that can be optimally exploited inside a subresonant cavity wherein all the available field modes have frequency greater than the atom's transition frequency. Earlier proposals [29–31] using density of field modes to relax acceleration requirement did not fully exploit the acceleration-induced spectral broadening as they focused on cavities tuned above the first resonance point, limiting the signal-to-noise ratio ($\tilde{\gamma}/\gamma_0 \lesssim 1$) that could be achieved in such setups, as analyzed in Figs. 4(a) and 4(b).

Response inside a subresonant cavity—The spontaneous emission rate of a single inertial atom placed between two perfect mirrors ($R \to 1$) is given as $\gamma_0 = (1/L)\sum_{n=1}^{\infty}\sin^2(n\pi/2)\Theta(1 - n\lambda_0/2L)$ [17], where $\Theta(x)$ is the Heaviside theta function. Note that γ_0 receives contributions from field modes with $n < 2L/\lambda_0$. In particular, if the separation between the mirrors is less than $\lambda_0/2$, there are no field modes available to facilitate spontaneous emission from the atom, leading to a vanishing γ_0 [32–34]. However, any realistic mirrors would have a reflectivity less than unity, and therefore the emission rate for $L < \lambda_0/2$ decreases smoothly with decreasing L [17].

On the other hand, due to acceleration-induced nonresonant behavior, a Rindler atom shows a stronger emission rate as the mirror separation is lowered below the first resonance point. Figure 3(a) compares the emission rates of an inertial and Rindler atom as a function of mirror separation and clearly shows a stronger emission rate of the Rindler atom below the first resonance point. As a result, in the subresonant configuration of the cavity, a large $\gamma_{\mathrm{a}}/\gamma_0$ ratio can be obtained. However, the emission rate for even an accelerated single atom in this cavity configuration is extremely weak. But, with many cooperatively behaving atoms ($\mu_{\mathrm{a}}N \approx \mu_0 N \gg 1$), which is possible at low accelerations with d/λ_0 lying in an appropriate range, the two rates can be superradiantly amplified. In flat spacetime, smaller interatomic spacing generally enhances the collective emission rate, provided that dephasing caused by coherent dipole-dipole interactions does not suppress the collective behavior [11]. The detrimental effects of these interactions can be mitigated by arranging the atoms in an orderly fashion such that each atom experiences a similar environment [11,35,36]. For example, ordered arrays [37,38] or ring configuration [35,36] would be suitable choices.

In Figs. 4(a) and 4(b), we plot the ratio $\gamma_{\mathrm{a}}/\gamma_0$ as a function of the mirror separation for different values of mirror reflectivity. For reflectivities $R < 1$, mirror separations $L > \lambda_0/2$ lead to $\gamma_{\mathrm{a}}/\gamma_0 \sim 1$, that is, $\tilde{\gamma}/\gamma_0 \ll 1$. However, for mirror separations $L < \lambda_0/2$ and for a given acceleration of the Rindler atom, the ratio $\gamma_{\mathrm{a}}/\gamma_0$ increases with higher mirror reflectivities, taking values as large as 50 for $R = 1 - 10^{-8}$, $a \sim 10^{-9}\omega_0 c$ (where we have momentarily restored c). Thus, the sub-resonant cavity

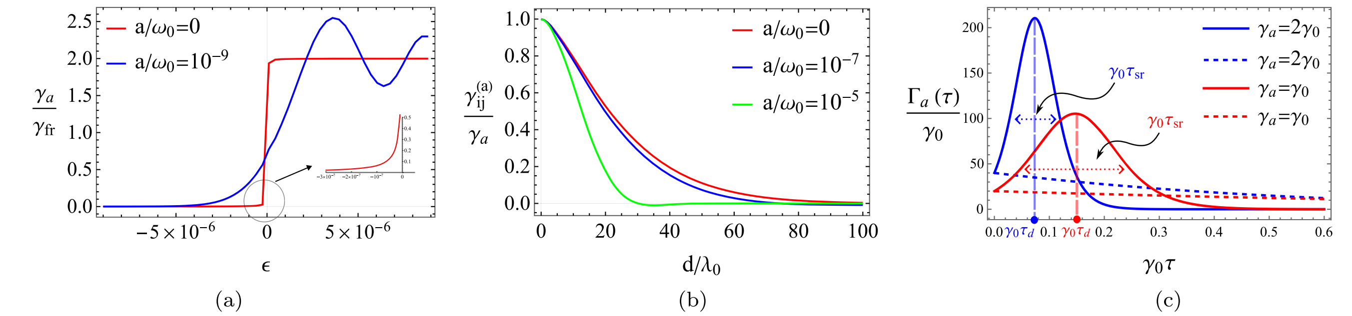

FIG. 3. Interplay of acceleration-induced spectral broadening and collective effects inside a subresonant cavity. (a) Behavior of the emission rate of an inertial and a Rindler atom as a function of the cavity detuning parameter ϵ (defined as $\omega_0 L = \pi + \epsilon$), for $R = 1 - 10^{-8}$. Here, γ_{fr} is the spontaneous emission rate of a single inertial atom in free space. For $\epsilon < 0$, that is $L < \lambda_0/2$, the emission rate of an inertial atom is highly suppressed, whereas the emission rate of a Rindler atom falls to the same extent for much lower mirror separation. (b) Impact of acceleration on $\gamma_{ij}^{(a)}/\gamma_{\mathrm{a}}$, the cooperation between i th and j th atoms, as a function of separation between the two atoms inside a subresonant cavity with $R = 1 - 10^{-4}$ and $\omega_0 L = \pi - 10^{-4}$. For a given separation between the two atoms, cooperation between them diminishes for increasing acceleration. (c) Comparison of the temporal behavior of the emission rate of an incoherent sample (dashed curves) of atoms versus that of a superradiant sample (solid curves), for $N = 20$. The temporal emission profiles of inertial and Rindler samples of independent atoms considerably overlap with each other in time. In superradiant samples however, the two signals can be resolved temporally as the superradiance process has a time-resolving nature characterized by the delay time τ_{d} and the superradiance time τ_{sr}.

configuration achieves $\tilde{\gamma}(\alpha)/\gamma_0 \gg 1$, as required. Moreover, in the same parameter range, $\mu_{\mathrm{a}}/\mu_0 \approx 1$ as shown in Fig. 4(c).

To summarize, combined with $\mu N \gg 1$, these conditions mean that the buildup of correlations among atoms, required for a superradiant burst, occurs faster in a Rindler array and is driven predominantly by the Unruh effect, as $\tilde{\gamma}(\alpha)/\gamma_0 \gg 1$. The field fluctuations perceived inertially under these conditions will be entirely inadequate to cause a superradiant burst in the given time. The early superradiant burst is thus entirely seeded by the modified field fluctuations underlying the Unruh effect experienced by the accelerated array of atoms—giving us a time-resolved and superradiantly amplified Unruh signal. A noticeable shift in τ_{d} due to the Unruh effect is easier to isolate experimentally than a shift in intensity only. Due to overlapping emission timescales, a collection of independent atoms cannot provide such a temporal resolution. Also, note that modeling superradiance merely as a perfect amplifier introduces ambiguities regarding the cause of the superradiant burst. Due to the tradeoff between acceleration requirement and the cavity quality factor (Table I), a burst seeded by the inertially perceived vacuum fluctuations can very easily be conflated with the one caused by the Unruh

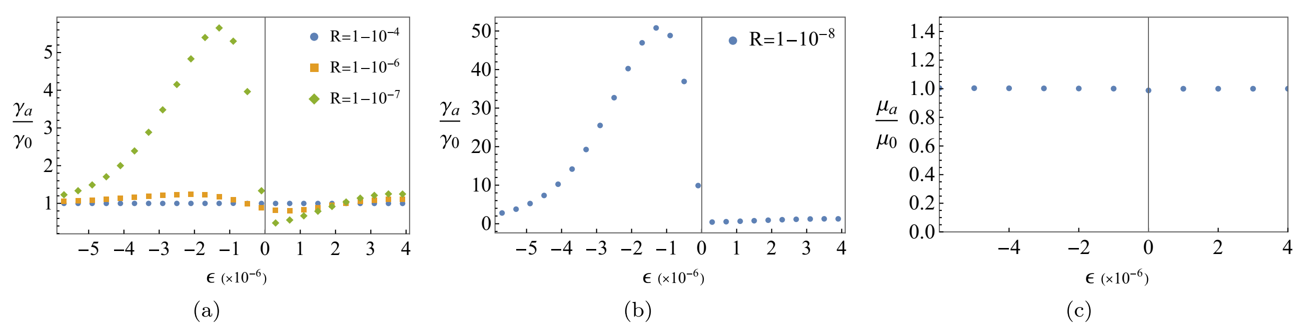

FIG. 4. Realization of conditions for time-resolution and superradiant enhancement of the Unruh signal inside a sub-resonant cavity. (a),(b) Dependence of $\gamma_{\mathrm{a}}/\gamma_0$ on the reflectively (equivalently, quality factor) and the cavity detuning parameter ϵ. Inside a sub-resonant cavity, higher mirror reflectivity leads to higher $\gamma_{\mathrm{a}}/\gamma_0$ values due to a stronger suppression of the emission rate of an inertial atom, while a Rindler atom still responds significantly due to the acceleration-induced non-resonant behavior. As $\gamma_{\mathrm{a}}/\gamma_0 = 1 + \tilde{\gamma}(\alpha)/\gamma_0$, unambiguously resolving the purely-noninertial signal $\tilde{\gamma}(\alpha)$ against the inertial signal γ_0 requires $\tilde{\gamma}(\alpha)/\gamma_0 \geq 1$, that is, $\gamma_{\mathrm{a}}/\gamma_0 \geq 2$. For $a/\omega_0 = 10^{-9}$, the two signals are not resolved unless the mirror reflectivity is equal to or better than $1 - 10^{-7}$, for which the two signals are well-resolved in a sub-resonant cavity configuration. This tradeoff between acceleration requirement and cavity's quality factor is elaborated in Table I. In (b), the required precision in the specification of cavity width to access $\gamma_{\mathrm{a}}/\gamma_0 \gg 1$ is $\Delta L/L \sim 10^{-6}$. (c) The ratio μ_{a}/μ_0 of the Rindler and inertial shape factors, for an atom array with $d/\lambda_0 = 1$, remains nearly constant over the cavity detuning range of interest. For all the plots, $a/\omega_0 = 10^{-9}$.

TABLE I. Requirement of extreme accelerations can be traded for high quality factor inside a precisely designed cavity. Minimum required quality factor, $Q_{\min} = 2\pi L\sqrt{R_{\min}}/\lambda_0(1 - R_{\min})$ [39], of the cavity mirrors to resolve the noninertial signal for various values of α. The Unruh signal can be resolved from the inertial signal at lower accelerations inside a precisely designed cavity if the cavity mirrors have a correspondingly higher quality factor.

$\alpha = a/\omega_0 c$	$R_{\min}$	$\omega_0 L/c = 2\pi L/\lambda_0$	$Q_{\min}$
10^{-11}	$1 - 10^{-9}$	$\pi - 10^{-8}$	$\pi \times 10^9$
10^{-10}	$1 - 10^{-8}$	$\pi - 10^{-7}$	$\pi \times 10^8$
10^{-9}	$1 - 10^{-7}$	$\pi - 10^{-6}$	$\pi \times 10^7$

effect. Therefore, as discussed in Supplemental Material [17], to employ the time-resolving nature of the superradiance process one must account for factors to which τ_{d} and τ_{sr} are intrinsically sensitive, these include cavity's finite quality factor, separation between the atoms, and dephasing due to coherent dipole-dipole interactions.

Implementation—The requirement of acceleration and the recent demonstration of robustness of collective effects in relatively noisy conditions in NV centers in a diamond membrane coupled to a high-finesse cavity [40] suggest that such solid-state platforms can be used to test for the early superradiant burst caused by the Unruh effect. An atomic transition frequency of the order of 10 GHz would be ideal as high quality factors ($Q \sim 10^9$) have been reported for cavities having resonance frequencies in the range of few to tens of gigahertz. Moreover, microwave resonator oscillators with a fractional frequency stability $\sim 10^{-16}$ have been demonstrated [41–46], giving an uncertainty $\lesssim 10^{-16}$ in the fractional length specification of the cavity. The idea of *time-resolution accompanying superradiant amplification* can be first tested in compact prototype experiments subjecting a collection of atoms to nonlinear accelerations [47–53], and potentially in analog systems [54–58]. In all these scenarios, the modified stronger field fluctuations experienced by the accelerated sample should lead to an early superradiant burst under appropriate conditions.

Conclusion—We have addressed three key challenges facing any potential experimental enterprise to observe the Unruh effect. The requirement of extreme acceleration can be traded for high quality factor inside a precisely designed subresonant cavity. By identifying conditions under which a superradiant burst is exclusively seeded by the Unruh effect, we theoretically demonstrated a highly amplified and temporally resolved Unruh signal. A clear separation in time between the Unruh and the inertial signals addresses the challenge of inertial noise overwhelming the purely noninertial signal. We thus identify laboratory conditions and tools that magnify the subtle observer-dependent field theoretic effects to a detectable level. Finally, the equivalence principle points to the gravitational analogs of the effects presented here—gravity-induced spectral broadening of atoms, and a collective quantum response seeded by gravity [9].

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N. A. and A. D. conceptualized the research. A. D. and N. A. performed the formal analysis and investigation. All the authors contributed to the interpretation and validation of the results and to the manuscript writing.

Data availability—The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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