Emergent Spacetime from Matter Emanations

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After long reflection in solitude and meditation, I suddenly had the idea, during the year 1923, that the discovery made by Einstein in 1905 should be generalised by extending it to all material particles and notably to electrons.

Louis de Broglie

Abstract

Einstein taught us that matter doesn't just move through spacetime; it actively bends and shapes the spacetime it inhabits. Building on this idea, we explore the possibility that De Broglie's matter waves can create an emergent spacetime, where space and time are intrinsic properties of matter. Along this journey, we uncover connections to quantum gravity and delve into how these insights can reshape our understanding.

1 Counting Ticks for Emergent Time

Recall that a massive particle with mass m, such as an electron, has a DeBroglie frequency $\omega = \frac{c^2}{\hbar}m$ [2]. We will discuss the number of "ticks", at frequency ω, that the particle has undergone from time t_1 to t_2 by unwrapping the phase of the particle and identifying the lifted zero crossings.

$$T_{t_1,t_2}(e^{i\omega t} \to t) = \{t \in [t_1, t_2] : t \in \frac{2\pi}{\omega}\mathbb{Z}\}$$

In this context, ω functions like a sampling rate or Nyquist rate for the matter in ticks per second. This concept parallels Bremermann's limit where the constant $\frac{c^2}{\hbar}$ represents ticks per second per kg.

We treat the number of ticks, $|T|$, as a quantum observable. In fact we may not know the bounds t_1, t_2 but can still sometimes talk about the distribution of number of ticks say between two events, like particle emissson and detection. The number of ticks is a wave function φ in the Hilbert space $H(T)$,

$$H(T) = \mathrm{Span}(|0\rangle, |1\rangle, \cdots)$$

It will act as an emergent representation of time for the particle. Since this time is relative to the particle itself, and not to an external observer, it resembles the concept of proper time. Next we move on to space.

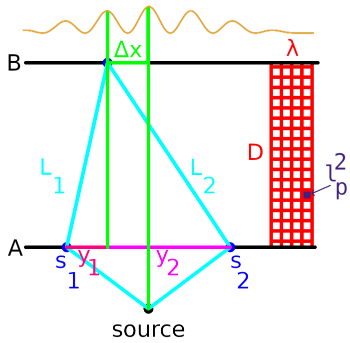

Figure 1: Typical double slit setup. D is the distance between screens A and B. $\Delta s = s_2 - s_1$ is the distance between slits. Δx is the distance between fringes. $\Delta L = \lambda$ is the difference of path lengths. $\frac{\lambda D}{l_p^2} = \alpha$ is a "count" of Planck length squares.

2 Double Slit for Emergent Space

Consider the situation in Figure 1. The particle of mass m is in quantum superposition, going through two slits, s_1 and s_2, on a one dimensional screen A. Let B be another screen behind A with distance D between them. Then for any time t and position x, causally beyond s_1 and s_2, we have the number of ticks n_1 with repect to s_1 and n_2 with repect to s_2. So (n_1, n_2) is a function of (t, x). Note that the interference patterns that appear on a screen B are given by fringes each of which can be labeled by a unique $k = n_2 - n_1$.

We can use this to describe how space emerges as a property of the massive particle by considering the Hilbert space for both paths jointly $H(T_1, T_2)$

$$\begin{aligned} H(T_1, T_2) &= H(T_1) \otimes H(T_2) \\ &= \mathrm{Span}(\{|i\rangle \otimes |j\rangle : i, j \in \mathbb{Z}_{\geq 0}\}) \\ &= \sum_{k \in \mathbb{Z}} \mathrm{Span}(\{|i\rangle \otimes |j\rangle : i, j \in \mathbb{Z}_{\geq 0}, i - j = k\}) \end{aligned}$$

and then considering the projection-valued measure $\{\Pi_k\}$ that picks out the space-like fringes k.

Let L_1 and L_2 be the lengths of the path from the source to the screen for the particle going through s_1 and s_2 respectively. Let the particle have a wavelength of $\lambda = \Delta L$ and we consider the first noncentral fringe, $k = 1$, at distance Δx away from the center. We have $L_i = \sqrt{y_i^2 + D^2}$ and approximating the square root we have $\lambda \approx \frac{\Delta s \Delta x}{D}$.

Consider the local behaviour of the interference pattern near the middle of B (the central fringe $k = 0$). The fringe pattern is locally made up of a combination of a part in space (fringes) and a part in time (particle evolution). Let $n_{1,2} = (n_1, n_2)$ label the antinodes of this pattern in space-time. The antinodes each pick out individual $n_{1,2}$ values, associated with the zero phase. We can write out a 2d joint frequency $\nu = \omega^2$ (in Hz * Hz) of this pattern using Δx and Δt. Using the mass energy of the particle $E_\hbar = \hbar\omega = \frac{\hbar}{\Delta t}$, we have

$$\nu = \frac{c}{\Delta x \Delta t} = \frac{c}{\hbar \lambda D} E_\hbar \Delta s \tag{1}$$

and

$$E_\hbar = mc^2 \tag{2}$$

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Following suit with Penrose[3] we let E_G approximate the gravitational (self) energy of the particle

$$E_G = \frac{Gm^2}{\Delta s} \tag{3}$$

Using the gravitational potential and setting m^2 equal to ω^2 times the squared Bremermann constant $c^4/\hbar^2$ we have

$$\nu = \omega^2 = \frac{c^4}{G\hbar^2} E_G \Delta s \tag{4}$$

We have written ν in two ways, equations (1) and (4). Setting these two representations of ν equal to each other we get

$$\lambda D = \frac{E_\hbar}{E_G} l_p^2 = \alpha l_p^2 \tag{5}$$

where l_p is the Planck length and we define $\alpha = \frac{E_\hbar}{E_G}$. Equation (5) suggestively counts Planck areas in λD as the unitless α:

$$\alpha = \frac{\lambda D}{l_p^2} \tag{6}$$

2.1 Escape Velocity, α, and Black Holes

We have another way of understanding α. By using equations (2) and (3) we have

$$\frac{1}{\alpha} = \frac{E_G}{E_\hbar} = \frac{Gm}{c^2 \Delta s} = \left(\frac{v_e}{c}\right)^2 \tag{7}$$

where v_e is an escape velocity. With this understanding we must have

$$E_\hbar \geq E_G \tag{8}$$

and the following are equivalent

1. Equation (8) is an equality.
2. Unitless $\frac{v_e}{c}$ is 1.
3. Unitless α is 1.
4. The particle is a black hole.

In the black hole case the suggestive count of α in equation (6) is related to the count of Planck areas on the event horizon of a black hole. To see this let the surface area of the black hole be $A = 4\gamma\lambda D$. Using black hole thermodynamics [1], we have an entropy S_{BH} with

$$S_{\mathrm{BH}} = \frac{A}{4l_p^2} = \frac{\gamma\lambda D}{l_p^2} = \gamma\alpha = \gamma \text{ (nats)}$$

2.2 Information and Acceleration

The treatment in this note extends to the less exotic $v_e < c$ case. For the Schwarzschild metric we have a unitless time dialation factor $\tau = \sqrt{1 - \left(\frac{v_e}{c}\right)^2}$. Using equation (7) we can use the unitless α to write

$$\tau = \sqrt{1 - \frac{1}{\alpha}}$$

3 TODO

1. $\hbar$ vs h
2. Entropy for general case?
3. What do the wavefunctions mean?
4. 3d case?

References

[1] Bekenstein, A. (1972). "Black holes and the second law". Lettere al Nuovo Cimento. 4 (15): 99–104. doi:10.1007/BF02757029. S2CID 120254309.

[2] de Broglie, Louis Victor. "On the Theory of Quanta" (PDF). Foundation of Louis de Broglie (English translation by A.F. Kracklauer, 2004. ed.). Retrieved 25 February 2023.

[3] Penrose, R. On the Gravitization of Quantum Mechanics 1: Quantum State Reduction. Found Phys 44, 557–575 (2014). https://doi.org/10.1007/s10701-013-9770-0