Close-orbiting black hole pairs are macroscopic quantum-gravitational systems

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Abstract. Close-orbiting pairs of near-equal black holes (M≈m) are a new kind of macroscopic quantum object because (I show) they have inherent mass-uncertainty $\Delta M_{total}>(M+m)/380$. These are the largest and heaviest macroscopic quantum systems ever found, the first observable physical system plausibly requiring quantum gravity for an accurate description, and the first which plausibly will enable learning about quantum gravity via direct observation.

Ingredient #1: Energy-time uncertainty principle

The vast majority of quantum mechanics textbooks say that $\Delta E\Delta t\geq\hbar/2$ where $\hbar\approx 1.055\times10^{-34}$ joule seconds, unfortunately *without* providing any precise meaning for ΔE or Δt and without telling the reader what, exactly, this supposed inequality even means. Fortunately, some precise statements are available. Bauer & Mello 1976 considered an unstable quantum system with "**survival probability**" **Q(t)** as a function of time t≥0, and **probability-density ϱ(E)** for its initial energy E. If the system were described by a wavefunction Ψ(x,t) then Q(t) with $0\leq Q(t)\equiv|\int\Psi^*(x,0)\Psi(x,t)dx|^2\leq 1$ is the probability the system remains in its initial state Ψ(x,0) after time t.

Define the "**Bauer-Mello timespan**" $\tau_{BM}\equiv(1/2)\int_{t>0}Q(t)^{1/2}dt$. For any system obeying the classic "exponential decay law" Q(t)=exp(-t/L) this definition would exactly yield its mean lifetime $\tau_{BM}=L$. And any Q(t) falling proportionally to $t^{-\gamma}$ (or faster) when t→∞, for any fixed exponent γ>2, will yield a *finite* τ_{BM}.

A measure of the energy-width of the system is $W_E=1/\max_E\varrho(E)$. The **Bauer-Mello theorem** then may be written $\tau_{BM}W_E\geq\pi\hbar/2=h/4$ or equivalently (which I prefer)

$$\max_E \varrho(E) \leq 4\,\tau_{BM} / h \quad \text{where} \quad h=2\pi\hbar\approx 6.626\times10^{-34} \text{ joule seconds.}$$

Bauer & Mello's constant 4 is *best possible* in the sense that their inequality becomes an equality in the classic exponential decay case Q(t)=exp(-t/τ) when the energy necessarily is described by the Cauchy density $\varrho(E)=2\pi^{-1}\Gamma/(4[E-E_0]^2+\Gamma^2)$ where Γ is the width of the energy-interval where $\varrho(E)\geq\max_E\varrho(E)/2=\varrho(E_0)/2$ and Γ and τ obey the **linewidth-lifetime relation** $\Gamma\tau=\hbar$.

Experimental confirmations: For the 134.24 keV excited state of Re-187, Mössbauer & Wiedemann 1960 measured the linewidth $\Gamma=(4.4\pm0.5)\times10^{-5}$eV using the Mössbauer effect (the line shape indeed is Cauchy to within measurement errors), deducing τ_{mean}=**15.2**±1.7 picoseconds. Blaugrund et al 1963 confirmed that prediction by measuring τ=**14.5**±2.0 ps using a microwave method. Steiner et al 1969 deduced τ_{mean}=**2.73**±0.02 nanoseconds from the Mössbauer linewidth of the 77.34keV level of Au-197 (superb fit to Cauchy lineshape in their fig.2), whereas delayed-coincidence timing found 2.65±0.029 (Gupta & Rao 1972) and 2.78±0.043 (Lynch 1973) which I combine to get **2.69**±0.05. This 1.5% agreement plausibly① is the best obtainable by Mössbauer methods. Steiner et al obtained their excited Au-197 by beta decay (719 keV) of Pt-197 (19.9-hour halflife) inside crystalline platinum. Their absorbers were gold foils of numerous precisely controllable thicknesses, allowing excellent extrapolation to zero thickness, all this at temperature 4.2°K. It helps that both Pt and Au have the maximally-symmetric FCC crystal structure (nearest neighbor distances 277 and 288pm) to help cancel out extra-nuclear fields; and that gold is fully soluble as a solid solution in platinum up to 100 atomic%. In hundreds of experiments, there has never been a case where any Mössbauer linewidth was *less* than $\hbar/\tau_{mean}$ by any significant number of experimental error bars. Thus *all* Mössbauer experiments support the validity of the Bauer-Mello *inequality*, while the above two support the precise optimality of their numerical constant. One to two orders of magnitude more precision came when Oates et al 1996 used trapped ultracold Na atoms to precisely measure the natural linewidth Γ=9.802±0.022 MHz= (4.054±0.009)×10^{-8}eV of the $3p^2P_{3/2}$ excited state, while Volz et al's adjacent paper measured its lifetime τ=**16.254**±0.022 nanosec using beam-gas-laser spectroscopy, agreeing within the experimental errors with the predicted $\hbar/\Gamma$=**16.237**±0.035 nanosec.

Other precise statements were obtained by Mandelstam & Tamm 1945, for example $Q(t)\ge\cos(t\Delta E/\hbar)^2$ when $0\le t\le(\pi/2)\Delta E/\hbar$ where $\Delta E\equiv[\int(E-\bar{E})^2\varrho(E)dE]^{1/2}$ and $\bar{E}\equiv\int E\varrho(E)dE$ and the integrations are over the full real line. In particular, if we define the "**half life**" $\tau_{1/2}=\min_{t>0}\{t \mid Q(t)\le 1/2\}$ then $\tau_{1/2}\Delta E\ge\pi\hbar/4=h/8$. The original textbook claim can be given this precise meaning: $\tau_{RMS}\Delta E\ge\hbar/2$ where $\tau_{RMS}=[\int_{t>0}Q(\sqrt{t})dt]^{1/2}=[2\int_{t>0}tQ(t)dt]^{1/2}$ is the **root mean square lifetime**. And if we define the "**mean life**" $\tau_{mean}=\int_{t>0}Q(t)dt$ then **GiSaWo** – Gislason, Sabelli, Wood 1985 – showed

$$\tau_{mean}\,\Delta E \ge 5^{-3/2}3\pi\hbar = 5^{-3/2}3h/2.$$

GiSaWo's constant also is best possible, in the sense that their inequality is tight when $\varrho(E)=(3/4)(1-E^2)$ for $|E|\le 1$, else 0. With that $\varrho(E)$ the survival probability Q(t) has $Q(t)t^4$ bounded below a positive constant always, but bounded above a (different) positive constant on a positive-density subset of the halfline t>0.

The four timespans we have discussed always obey $0<\tau_{1/2}\le\min(2\tau_{mean}, 2^{1/2}\tau_{RMS}, 2^{3/2}\tau_{BH})$ and $\tau_{mean}\le 2\tau_{BH}$, $\tau_{mean}\le\tau_{RMS}$. [The first arises from Markov's inequality in probability theory; the second from Hölder's (1,∞) inequality, and the third from the concave-∪ nature of the squaring function.]

It now is natural to ask whether there is any uncertainty relation *combining* the virtues of *both* GiSaWo and Bauer-Mello, i.e. of the form $\max_E \varrho(E)\le\varkappa\tau_{mean}/h$ (or $\le\varkappa\tau_{1/2}/h$) for some positive constant $\varkappa$. The answers both are **no**, because the probability density $\varrho(E)=\pi^{-1/2}\Gamma(v+3/2)\Gamma(v+1)^{-1}(1-E^2)^v$ for $|E|<1$, else 0 (where v>-1 is a constant) corresponds to a survival probability Q(t) with $Q(t)t^{2v+2}$ bounded below a positive constant always, and above another positive constant on a positive-density subset of the halfline t>0. That's due to, e.g, EQ 2-7-19 of Sneddon 1972. So if -1<v<0 then $\max_E \varrho(E)=\infty$, while if -1/2<v then both $\tau_{1/2}$ and τ_{mean} are

finite and positive. So any v with $-1/2<v<0$ yields a counterexample. I do not know whether there is any uncertainty relation of form $\max_E \varrho(E) \le \varkappa \tau_{RMS}/h$.

However, I can prove (but[2] will not here) $\tau_{mean}\Delta_1 E > 0.2889\hbar$ and more generally for any fixed $k>0$ that $\tau_{mean}\Delta_k E > c_k\hbar$ where $\Delta_k E \equiv [\int |E-\bar{E}|^k \varrho(E) dE]^{1/k}$ and the c_k are appropriate positive constants. I can also prove: If the narrowest energy interval containing at least 31% probability $[\int \varrho(E)dE \ge 0.31]$ has width $W_{31\%}$, then $\tau_{1/2}W_{31\%} > 0.005969\hbar$.

For **exact-exponential** decay $\tau_{1/2}/\ln 2 = \tau_{mean} = \tau_{BH} = 2^{-1/2}\tau_{RMS}$; and $\Delta_k E$ is finite for each k with $0<k<1$, for example $\tau_{mean}\Delta_{1/2}E = \hbar$ and $\tau_{mean}\Delta_{2/3}E = 2^{1/2}\hbar$; and $W_{31\%} \approx 0.5295\hbar/\tau_{mean}$; but $\Delta_k E = \infty$ for each $k \ge 1$. That infinity is one reason that exact exponential decay is, under traditional quantum mechanics, considered impossible (Fonda et al 1978); but if, say, radium decays exponentially for 300 halflives then switches to $t^{-\gamma}$ style decay for some exponent γ with $2<\gamma<5$ (which is roughly what most analysts contend), then (a) those infinities would not arise, and (b) detecting this departure from exponentiality would be infeasible.

Ingredient #2: Gravitational radiation from rotating quadrupoles

Two rotating systems are

a. Uniformly-dense rigid thin rod of length=L and mass=M rotating about an axis perpendicular to the rod through its midpoint.
b. Two point masses m and M, separated by distance L, both circularly orbiting their center of mass (either because joined by a massless length-L rod, or because of their mutual gravitational attraction according to Newton's laws).

Let the angular velocity be Ω, so the period is $2\pi/\Omega$. Either way, we have a "rotating quadrupole" which therefore **emits gravitational-wave radiation**.

In case (a) Eddington 1922/1923 (where we've also used the formula $I=ML^2/12$ for the moment of inertia I of the rod) calculated the emitted power

$$P_{rod} = 32GI^2\Omega^6c^{-5}/5 = 2GM^2L^4\Omega^6c^{-5}/45.$$

(The reason Eddington published this twice, using two different methods, was to become confident that Einstein previously had been a factor of 2 too small.) This corresponds to a rate of emission of gravitons (each graviton having angular frequency 2Ω) with mean time τ between graviton emissions equal to $\tau = 2\hbar\Omega/P = 45\hbar G^{-1}M^{-2}L^{-4}\Omega^{-5}c^5$. See Smith 2021 for analysis of the claim "gravitons exist" and with energy $E=hf$ for a frequency=f graviton. (And if 2Ω were only an *upper bound* on graviton frequency, then our formula would only upper-bound τ, which would be adequate for the purposes of this paper.) If we now regard the rotating rod as a *quantum* system with mean decay time τ, we see from the GiSaWo bound and $E=mc^2$ that the mass of the rod necessarily is *uncertain*, with $\Delta M \ge 5^{-3/2}3\pi\hbar c^{-2}/\tau$, that is, $\Delta M_{rod} \ge (5^{-5/2}\pi/3)GM^2L^4\Omega^5c^{-7} = 5^{-5/2}48\pi GI^2\Omega^5c^{-7}$.

Case (b) can be treated using the more general analysis in §10.5 of the book by Weinberg 1972, but Eddington's I-based formula also works given that our two masses M and m have respective distances R and r to their center of mass, whereupon solving MR=mr and R+r=L for r=LM/(m+M) and R=Lm/(m+M) determines the moment of inertia $I=mr^2+MR^2=L^2mM/(m+M)$. The radiated power is $P_{binary}=(32/5)Gm^2M^2(m+M)^{-2}L^4\Omega^6c^{-5}$. If the masses obey the Kepler-Newton law $(m+M)G=\Omega^2L^3$ then the radiated power can be rewritten as $P_{binary}=(32/5)m^2M^2(m+M)L^{-5}G^4c^{-5}$. Then as before we find $\tau_{binary}=2\hbar\Omega/P_{binary}=(5/16)\hbar G^{-7/2}M^{-2}m^{-2}(m+M)^{-1/2}L^{7/2}c^5$ and $\Delta M_{binary}\ge 5^{-5/2}432\pi c^{-7}G^{7/2}M^2m^2(m+M)^{1/2}L^{-7/2}$.

Without loss of generality 0<m≤M. Now suppose that the center-separation L happens to be near minimum possible. The Schwarzschild radii of the two masses in isolation would be $r=2mGc^{-2}$ and $R=2MGc^{-2}$. So clearly if $L\le r+R=2(m+M)Gc^{-2}$ then our "two" black holes would actually be one merged entity. The Newtonian equipotential surface at the same potential as a single isolated hole's horizon (corresponding to escape velocity=c for an infinitesimal test mass) becomes topologically *two* spherical surfaces exactly when L satisfies L>x+X with $M/X+m/x=c^2/(2G)$ and $MX^{-2}=mx^{-2}$. It is simplest to solve these equations when m=M (hence r=R), the answer then being $L>2x=2X=4R=8MGc^{-2}$. The fully-general answer is $L>2([m/M]^{1/2}+1)(m+M)Gc^{-2}$. Of course, our uses of the "Newtonian potential" and the "Kepler-Newton law" both are only approximately valid since we have ignored general relativistic time dilation, space distortion, and dynamics. So the reader should keep in mind that all our formulas about black holes at near-minimal separation are only **approximate**, i.e. are the leading order terms in the "post-Newtonian" sequence of approximations. This still must yield a *lower bound* on radiated power, valid to within a dimensionless constant factor. (For more accuracy one could use Will & Wiseman 1996's "second post-Newtonian order" calculation; and to get the constant presumably arbitrarily near exact, one could do computer simulations ala Healy & Lousto 2017.)

If our two masses indeed are black holes separated by that approximate minimum possible distance, then the radiated power becomes

$$P_{binary} = m^2\, M^2\, (m+M)^{-4}\, ([m/M]^{1/2}+1)^{-5}\, P_{Pl} / 5$$

where $P_{Pl}\equiv c^5/G\approx 3.6283\times10^{52}$ watts is the **Planck power unit**. Therefore if m≈M then P_{binary} is about $2^{-9}5^{-1}=1/2560$ Planck power units, i.e. about 1.4173×10^{49} watts, *regardless* of m+M.

Comparison vs. Experiment: The table lists seven LIGO-detected black hole mergers enjoying comparatively high-quality data and analyses, and with primary/secondary mass ratios all fairly near 1.

The peak power was always between 27 and 40 in units of 10^{48} watts, showing as expected a noisy *decreasing* trend with mass ratio. The lost/total mass ratios were always between 3% and 6%. The apparent *constancies* of peak power and lost/total for fixed primary/secondary mass ratio, despite total mass varying by an order of magnitude, agree with what our model predicts. The observed numerical *values* of the peak power, however, are a factor somewhere between 2 and e times our model's prediction. We have several valid excuses for that:

1. As we'd said, our model makes Newtonian *approximations*, which become poor as we approach (and ridiculously poor after) horizon merger.
2. Our model ignored the fact that actual black holes have different *spins*, simplistically regarding all black holes of a given mass as identical.
3. *After* topological merger occurs, gravitational waves will *still* radiate while the event horizon changes from a goofy dumbbell shape into its ultimate nice round Kerr shape. That relaxation might well involve greater energy-loss and/or more power than the pre-merger stage, but my model is *only* applicable pre-merger.

Event name	Masses (suns)	Lost mass	Lost/Total	Prim/Sec	Peak power (10^{48}W)	Comments
GW190521	150=85+66	7.6	5.1%	1.29	37±8	60Hz for 100msec (4 cycles)
GW170814	56=32+24	2.7±0.35	4.8%	1.33	37±5	
GW200202	17.6=10.1+7.5	0.82	4.7%	1.35	?	
GW150914	68=38.7+32.5	3.1±0.4	4.6%	1.19	35±5	1st detected; 50M CPU hours for simulations
GW170608	19=12+7	0.85±0.12	4.5%	1.71	34±11	
GW151226	21.8=14.2+7.5	1.0±0.15	4.6%	1.89	33±12	
GW170104	48.7=31.2+19.4	2.0±0.65	4.1%	1.61	31±10	

And indeed, **computer simulations** by Healy & Lousto 2017 predict that the maximum possible peak power (which happens near the time of horizon-merger; they did not say whether before or after) occurs for equal-mass black holes, each with maximum spin aligned with orbital angular momentum, and equals 7.1368×10^{49} watts, i.e. 5.0355 times our prediction, a ratio suspiciously near both 5 and $(5\pi/7)^2\approx5.035512$. Even greater power might be possible if the two holes were oppositely electrically *charged*, since then photons also would be radiated. But astrophysical holes presumably are near-neutral, a hypothesis supported by the non-observation of giant EM-radiation pulses from hole mergers. Their same peak-power-maximizing scenario also maximizes the fraction of total initial mass ultimately radiated, i.e. lost: 11.3%. The *minimum* loss fraction (≈3%) in the equal-mass case occurs for maximum hole spins *anti*-aligned with orbital angular momentum. In the spinless equal mass case their peak power is 3.7226×10^{49} watts, i.e. $2.6265\approx2\ln(1+e)$ times our model's prediction, with 4.857% of the initial mass allegedly radiated. This all makes it clear our Newtonian model **underestimates** peak power.

We now use our peak-power formula to deduce the mean time τ between graviton emissions $\tau_{binary}= 2^{-1/2}5\hbar c^{-2} M^{-2}m^{-2}(m+M)^3 ([m/M]^{1/2}+1)^{7/2}$ which when m=M is $\tau_{binary}=320\hbar c^{-2}m^{-1}$. Then via the energy-time uncertainty principle (GiSaWo bound) and $E=mc^2$, the uncertainty ΔM in total mass is lower bounded by $\Delta M_{binary} \geq 5^{-5/2}2^{1/2}3\pi M^2m^2(m+M)^{-3} ([m/M]^{1/2}+1)^{-7/2}$ which when m=M becomes

$$\Delta M_{binary} \geq (5^{-5/2}2^{-6}3\pi) (M+m) \approx 0.002634 (M+m) > (M+m) / 380$$

regardless of c, G, and $\hbar$.

If, further, we assumed the inter-graviton time delays were approximately *exponentially* distributed, then we could increase the constant 0.002634 in the lower bound, e.g. using the half-life inequality $\tau_{1/2}\Delta E \ge \pi\hbar/4$ instead of GiSaWo would increase it to 0.00354. Indeed, it would increase to arbitrarily large values under the (false) assumption of arbitrarily precise exponentiality. I suspect that exponentiality should be quite precise because gravitons are being emitted at the huge rate $\tau^{-1}\approx 10^{88}$ per second for M+m=10^9 solar masses – by far the greatest particle-emission rate I ever saw for anything – with chronologically-adjacent graviton-emissions from source locations $\gtrapprox c\tau \approx 10^{-79}$ meters apart presumably *independent*. Hence I expect probability correlations of order 10^{-180}. Therefore the graviton emission times presumably well-approximate a Poisson process. Poisson process gap lengths are exactly exponentially distributed. Therefore I expect our lower bounding constant 0.002634 is extremely conservative (and of course would be multiplied by 5.0355 if we used Healy & Lousto's peak power formula instead of our model's), with the truth probably somewhere between **0.04 and 0.6**.

Remarkable Conclusion

Two closely orbiting comparable-mass black holes always form a *quantum* system, whose inherent mass *uncertainty* necessarily exceeds 1/380 of its total mass. This is by far the largest intrinsic mass-uncertainty I ever heard of for anything macroscopic. This can be (which presumably has happened many times) a "macroscopic quantum phenomenon" weighing 10^9 solar masses, with diameter comparable to the solar system, with mass-uncertainty exceeding millions of solar masses – all again by far the largest I ever heard of – lasting for months③. As far as I know no prior author has ever pointed out that black holes, despite their giantness, can be *quantum* in nature and **require**④ quantum gravity for accurate description. In fact, **this is the first physical system anybody ever thought of, in which quantum gravity plays such a large role that it should be feasible to "observe" it in action**. And given the recently developed capability of the "event horizon telescope" to "see" certain black holes with high resolution, and LIGO's ability to "hear" black hole mergers in real time, this for the first time opens up serious hope that it might be possible to learn about quantum gravity *by direct observation*.

Discussion

To see just how remarkable this is, let us compare it versus various other systems.

The rod-shaped interstellar asteroid "Oumuamua" has L≈400 meters, rotation period≈8 hours so $\Omega\approx 2\times 10^{-4}$/second, and if made of iron has mass $M\approx 4\times 10^9$ kg. I compute $\Delta M\approx 8\times 10^{-61}$ kg. If we replaced the iron by high strength steel and sped up the rotation period to 3 seconds (any faster and steels would not be strong enough) then τ=10 picoseconds and $\Delta M\approx 9\times 10^{-41}$ kg, which still is 10 orders of magnitude smaller than the mass of a single electron.

BAT99-98 in the Large Magellanic Cloud arguably is the most luminous star currently known. It is believed to have mass 226 times our sun, luminosity≈1.9×10^{33} watts equivalent to 5×10^6 suns, and surface temperature 45000°K. I deduce that it emits about 10^{51} photons per second. If we regard this entire star as a quantum system with decay time 10^{-51} second, then its inherent mass-uncertainty is $\Delta M\approx c^{-2}\hbar 10^{51}$/second≈1 kg. Peak supernova luminosities can reach 5×10^9 suns (1.9×10^{36} watts), suggesting by the same calculation

ΔM of order ≤1000 kg. That still is peanuts in the sense that $\Delta M \leq 10^{-28} M$ is far too small to detect.

The tininess of those ΔM's was not merely due to luck.

1. We can readily argue that the graviton-emission-caused ΔM of *every* rotating gravitationally-bound system is (as a fraction of its total mass M) *maximized* when it is a black-hole close binary system – and if it does not involve at least 2 black holes, is always much smaller.

2. For simplicity in the following argument let me work in Planck units ($\hbar=c=G=k_B=1$) and ignore constant factors of order 1. Consider a Euclidean ball of radius=R with at least the outer layer (layer thickness λ) of this ball consisting of hot material (temperature $T\approx 1/\lambda$). Regard this as a quantum system which "decays" by emitting photons, e.g. of blackbody radiation at temperature≈T and wavelength≈λ into the region outside the ball. The "decay time" (i.e. mean time between such photon emissions) will then be of order $R^{-2}T^{-3}\lambda$. This decay time will cause our system to have ΔM of order R^2T^3/λ. Meanwhile the mass M of that outer layer is at least of order $R^2T^4\lambda$. Hence $\Delta M/M \approx T^{-1}\lambda^{-2} \approx T$. We conclude that ΔM/M has order≥1 *only* when the temperature T is at least of order 1 Planck temperature unit: $T \geq T_{Pl} \approx 1.417\times10^{32}$°K. However, that assumed Euclidean geometry. In fact, $T<R^{-1/3}$ is necessary otherwise our ball will be so heavy it is a black hole (and therefore not emit radiation at all). Therefore, ΔM/M of order ≳1 is *impossible* for any system of our "**hot ball**" type whose radius R exceeds order 1 Planck length units: $R>L_{Pl}\approx 1.616\times10^{-35}$ meters.

Particle	Mass (MeV/c^2)	Est.Mean Lifetime (sec)	ΔM/M	(lost mass)/M
Roper resonance	1370	3.7×10^{-24}	0.11	0.315
$W^{\pm}$ boson	80377±12	3×10^{-25}	0.02301	
Z^0 boson	91187.6±2.1	3×10^{-25}	0.02028	
Top quark	172760±300	5×10^{-25}	0.00642	0.535
Lithium-4	3751.304±0.002	1.31×10^{-21}	0.000113	0.251
Higgs boson	125110±110	$(1\text{-}5)\times10^{-22}$	0.00004435	
Tauon	1776.86±0.12	$(2.903\pm0.005)\times10^{-13}$	10^{-12}	
short kaon K^0	497.611±0.013	$(8.954\pm0.004)\times10^{-11}$	10^{-14}	0.7
kaon $K^{\pm}$	493.677±0.016	$(1.238\pm0.002)\times10^{-8}$	9×10^{-17}	
long kaon K^0	497.611±0.013	$(5.116\pm0.021)\times10^{-8}$	2×10^{-17}	
Polonium-212	197466.38	4.31×10^{-7}	7×10^{-21}	0.0189
Cobalt-60	55828.0019	2.4×10^{8}	4×10^{-35}	5.06×10^{-5}
Curium-250	232947	3.8×10^{11}	6×10^{-39}	0.5
Bismuth-209	194664	9×10^{26}	3×10^{-54}	0.0192
Tellurium-128	119142.2	10^{32}	3×10^{-59}	7.285×10^{-6}

3. The table shows some of the fastest-decaying unstable particles known, and computes their $\Delta M/M$ from their mass M and estimated mean lifetime τ via the GiSaWo bound. The "Roper resonance" (Burkert & Roberts 2019) is the first excited state of the proton. The isotopes from cobalt-60 onward (not ultrashort-lived) are included merely for comparison purposes. We also tabulate "lost mass," the mass difference between the heaviest decay product and the initial mass (in cases with sufficiently-unique decay reaction) merely to demonstrate its non-relationship to the mass *uncertainty* ΔM.

4. The lifetime of a composite of N identical subsystems should be of order 1/N times the subsystem lifetime, my point being that $\Delta M/M$ is *unaffected* by N-fold cloning. If the subsystems are *independent* one could perhaps argue the net ΔM should be smaller than the sum of the N component ΔM's (e.g. only about $N^{1/2}\Delta M$) due to partial cancellations. Either way, any system made of the above-tabulated (or any other known) particles should have $\Delta M/M \ll 1$.

5. Obviously, every normally-encountered macroscopic object has undetectably small inherent mass-uncertainty, $\Delta M \ll 10^{-20} M$.

In view of 1-5 above, it seems reasonable to **conjecture** that

A. No macroscopic physical system can ever have greater $\Delta M/M$ than two close-orbiting near-equal black holes.
B. And the only physical systems whose $\Delta M/M$ values can compete are some of the most-unstable subatomic particles (which, of course, are inherently *quantum* objects), the best one I know being the (currently poorly understood) "Roper resonance."
C. Two close-orbiting near-equal black holes are an inherently *quantum* macroscopic system, innately requiring *quantum gravity* for precise treatment④.

Now we must ask – to use a technical term – what the hell?!?!

"Macroscopic quantum phenomena" (**MQP**) can be weird and mysterious. The two most familiar are *superconductivity* and *superfluid* liquid helium. I suspect that if these two phenomena had not been discovered by accident, then no theorist would have been smart enough to predict them. As it was, H.K.Onnes discovered in 1911 that mercury superconducts below about 4°K. It took until about 1961 (50 years later) before Bardeen, Cooper, Schrieffer, and Eliashberg (BCSE) gained (what some contend to be) theoretical "understanding" of that – although those 4 people remained not smart enough to predict the Josephson effect. This understanding, however, even as of year 2023 remains rather pathetic. If we had real understanding, then a supercomputer could mentally search all possible ≤6-atom chemical compounds and tell us the predicted best (e.g. highest T_c) superconductor. But that never happened; essentially all decent superconductors have been found by experimenters operating on hunches or by random trials, with near-zero quantitative theoretical help. And even BCSE far exceeds present understanding of the high-T_c cuprates. Incidentally, superconductor T_c's are not related to $\hbar$ in any simple way, unlike (say) their [Fermi temperature] – much like our black hole $\Delta M/M$'s independence from $\hbar$.

Superfluidity in liquid helium below 2.17°K was first discovered in 1937 and more-or-less explained within 30 years, but some questions remained disputed/unclear even as of ≈2018, such as the existence of "supersolids."

My point with this historical retrospective is that despite 50-100 years of theoretical *and* experimental examination, neither superfluidity nor superconductivity are understood nearly as well as we would like. Given this historical proof of human incompetence about MQP – and close black hole binaries are a completely new kind – plus our clear present incompetence about quantum gravity, I am unwilling to assert that I know what is going on.

As far as I am aware, the LIGO team until now has believed (LIGO GR-test papers 2019-2022) that all their data has been 100% compatible with non-quantum general relativity. I now advise them to gather that data more accurately and analyse it more!

How can we interpret this in human terms? I can only say a little. Although you might survive repeated shootings if given enough time to heal between shots, you will disintegrate if machine-gunned by a tremendous number of bullets. What is happening here is the destruction of the deterministic nature of spacetime geometry, when machine-gunned by a too-huge flux of a too-tremendous number of gravitons.

What is something that huge with that much mass quantum-uncertainty like? The GW150914 merger involved the inspiral of two holes of masses 39 and 32 suns (radii 115 and 95km), about 1.3×10^9 lightyears away from here, reaching maximum speed ≈0.6c, and radiating high power for about 0.2 seconds. The gravity waves from this event distorted lengths on Earth by factors $\pm10^{-21}$, but 1000km from the merger those distortions were ±1%. If a human went anywhere near black holes like those, i.e. with anywhere near stellar mass, then the tides would "spaghettify" and kill him. However, tides near *supermassive* holes are survivably small even at the event horizon. A human subjected to oscillating ±1% length distortions in an intense gravity wave would suffer shattered bones if the frequency of the wave were too high versus the characteristic acoustic frequencies of that bone, perhaps 3700 Hz for an adult femur, so that they could not readjust in time. But wave frequencies from super-super mergers would be very low, giving you plenty of time to readjust, suggesting this would not pose a problem. So as far as *non*quantum effects are concerned, you should be able to survive being right near a super-super merger, the most energetic event in the universe! However, lifeforms and engineered mechanisms have always been able to take for granted the deterministic nature of lengths and times to extremely high accuracy. Near a binary black hole with relative mass uncertainty $\Delta M/M\in(1/380, 0.6)$, lengths and times also should exhibit the same-order inherent relative uncertainties. I do not know how lifeforms would react to or perceive an environment like that.

Contrast vs. Hawking: Hawking radiation is something that gets "more quantum" (e.g. hotter, more power) the *tinier* the black hole. But my black hole pair mass-uncertainty gets "more quantum" (e.g. lasts longer, shorter intergraviton timespans during each of which total energy is highly uncertain) the *larger* the holes.

What happens inside the hole? Time outside a Schwarzschild-metric's event-horizon proceeds forward, while time inside it points radially inward (which is why anybody incapable of backward time-travel cannot escape from the hole). The horizon itself is a "null surface" which "does not experience time." Long (as regarded by faraway observers) waves become infinitesimally short on Schwarzschild horizons due to infinite blueshift factors. So: can the quantum length-uncertainties which occur merely *temporarily* around merging from the standpoint of an external observer, get blueshifted to microscopic size then "frozen" onto the horizon, thereby causing the spacetime metric inside the final hole to be quantum-weird *permanently*?

My new MQP **might "not matter."** Why? **(a)** Regard the black hole binary as an unstable quantum system, *but* each time it radiates another graviton, we get a *new* such system. If all these systems were "independent" in some suitable sense then their mass uncertainties might, if observed "blurred" over long time spans (say

10^{20} graviton-emissions) largely **cancel** out, e.g. effectively reducing ΔM by a factor 10^{10}. (And indeed, notice that the claimed experimental error bars on some of our tabulated particle masses are considerably smaller than their inherent uncertainties, which is mainly due to averaging over many observed particles.) But, at least naively, it seems as ridiculous to argue for such "independence" as it would be to argue that the Earth, after emitting one photon, reaches a state "independent" of its prior state – indeed, considerably *more* ridiculous if we want the *mass* to become a random deviate "independently" re-sampled from a distribution with standard deviation 10^6 solar masses, after each single graviton emission. I currently have almost no clue to what extent the "independence/blur/cancel" hypothesis is valid or useful; and to what extent, and how, the largeness of ΔM/M "really matters."

(b) We noted the unusual peculiarity that the peak "quantum uncertainty" ΔM in mass, does **not depend on** $\hbar$. Usually, "quantum effects" go to zero when $\hbar \to 0$. Does this mean this quantum uncertainty is "really not quantum" somehow? And is it related to the "lost mass" (which also does not depend on $\hbar$, and has the same order of magnitude as ΔM)?

My answers: First, that was far too facile: our ΔM/M formula also is independent of c and G, but it would be absurd to contend it is "not really relativistic or gravitational." Second, at least for general decaying systems, lost-mass and mass-uncertainty clearly are very unrelated, and the derivation shows my peak ΔM really is quantum in origin despite ΔM/M's lack of dependence on $\hbar$. (Actually it *does* involve $\hbar$, but in two ways, which cancel.) Third, the ΔM and lost-mass concepts differ greatly in their time-behavior. For $M \approx 10^9$ suns, it takes months to lose that mass; but the mass-uncertainties ΔM arise on time scales 10^{-88} seconds.

Are those non-dependences on $\hbar$ merely artifacts of my model being the leading order post-Newtonian approximation, so that $\hbar$'s would appear in higher-order correction terms? No: I claim peak ΔM/M is independent of $\hbar$ at *all* orders in the postNewton expansion. Why? General relativity (GR) obeys the *scale invariance* property that scaling up all masses, lengths, and times by an arbitrary factor s, leaves GR unaltered. Hence the power P radiated is s-invariant, while the frequency F scales like s^{-1}, hence the mean timegap $\tau = hF/P$ between graviton emissions will scale like h/s, hence peak ΔM will scale like hc^{-2}/τ which (like M) scales like s – and note the h has canceled out – so peak ΔM/M is both $\hbar$ and s-invariant. Q.E.D. Since the "lost mass" also is s-invariant for any standardized hole-inspiral scenario, we see⑤ that peak ΔM/M and ultimate (lost mass)/M indeed will be the same for our problem, up to a factor that is an evidently-nonconstant function of initial-spin data.

Perhaps **scale invariance is a *hallmark* of macroscopic quantum phenomena**, indeed exactly what permits them to reach macroscopic size. You might object that the entire description of superfluid liquid helium certainly is not scale-invariant. Yes, *but* the key parameter, the number density of helium atoms times the cubed thermal wavelength of one such atom, *is* unchanged (at any fixed temperature) by getting a bigger bottle of liquid helium. Another example is a single photon: its ΔE/E is invariant on scaling to long wavelengths, and does not depend on $\hbar$.

To conclude: that $\hbar$-independence indeed looked suspicious a priori, but seems less so a posteriori. Anybody still wanting to decry our ΔM/M as "not really quantum" probably would need to make major advances in "interpretation of quantum mechanics" before hoping to convince anybody.

(c) Suppose the mass of the black hole binary somehow keeps getting "**measured**" extremely frequently, thereby preventing it from being very uncertain. The concept of quantum measurement has always been mysterious... and it is hard to imagine how measurements could happen at any enormous-enough rate... but anyhow this is another conceivable way our effect might "not matter." On the other hand that very measurement *itself* might be a quantum-gravitational effect, in which case quantum gravity *would* "matter."

There simply is zero prior experience with any macroscopic system featuring nonnegligible $\Delta M/M$. All I can say for now is: this certainly seems worthy of investigation.

Endnotes

①: Mössbauer lines with lifetimes>100ps and hence linewidths<6.6×10^{-6}eV usually get substantially broadened by extranuclear fields hence rarely can match Re-187's accuracy. A countermeasure is to embed your isotope inside a suitably *symmetric* nonmagnetic crystal (e.g. Fe-57 inside ferrocyanides). That can work well for absorbers, but for emitters you also need the (chemically different!) parent isotope to be embedded in the same way, and for all that not to be wrecked when the parent disintegrates – difficult. Decker & Lortz [J.Appl.Phys. 42,2 (1971) 830-833] used both the ferrocyanide, plus the "multiple absorber thicknesses" trick enabling *separate* determination of the absorber and emitter linewidths (not merely their sum), to find in their Table III only 30% greater Mössbauer linewidth than deduced from Kistner & Sunyar's [Phys. Rev. B 139,2 (1965) 295] directly-measured mean life 140ns for the 14.41keV excitation of Fe-57. Better – 18% and 16% – agreements: τ_{Mossb}=131±4ps versus τ_{direct}=154±33ps for the 129.4keV Ir-191 line, and τ_{Mossb}=267±6ps versus $\tau_{Coul.excit.}$=308±16ps for the 46.48keV W-183 line. [Data sources: Bullard et al: Phys.Rev.B 43,10 (1991) 7405, Baglin: Nucl.Data Sheets 134,4 (2016) 149, Mössbauer: Z.Naturforschung A 14 (1959) 211, Steiner et al 1969, Wagner et al: Phys.Rev.Lett. 28,9 (1972) 530, Owens et al: Phys.Rev. 185,4 (1969) 1555, Lindskog et al: Zeitschr.f.Phys. 170,3 (1972) 347, Malmskog & Bäcklin: Arkiv Fysik 39 (1969) 411, Narismha Rao & Jnanananda: Proc.Phys.Soc. 87,2 (1966) 455, Berlovich et al: Sov.Phys.JETP 16,5 (1963) 1144.]

②: Proofs available on request.

③: About 50 black holes have been found in our galaxy, plus about 150 supermassives with confirmed mass measurements in other galaxies, plus over a million less-studied quasars. There are 3.5×10^{11} galaxies in the observable universe based on correcting galaxy counts from the "Hubble extreme deep field" image with dark-sky optical background measures by Lauer et al 2021 from the New Horizons spaceprobe. It's estimated there are over 10^8 holes in our galaxy alone and 4×10^{19} in the observable universe (Sicilia, Lapi et al 2022); and that average galaxies contain ≈1 supermassive hole, suggesting there are 3.5×10^{11} supermassives in the observable universe. Ours, "Sagittarius A*," has mass≈4.2×10^6 suns, while perhaps the heaviest presently known is TON 618 at 6.6×10^{10} solar masses. The Schwarzschild radius 19.7 AU of a 10^9-sun black hole is comparable to the Sun-Neptune distance 28.9 AU. Two big holes, currently ≈1600 light-years apart in the galaxy NGC 7727 and massing 6×10^6 and 154×10^6 suns, are forecast to merge within the next 250 Myr. The blazar OJ 287 is believed based on optical periodicity observed over 100 years, and other observations including very long baseline interferometries dating back to 1995, to be a binary supermassive with redshifted orbital period≈12 years, with component masses (depending on the modeler) each somewhere between 10^8 and 2×10^{10} solar; one merger forecast was only 10^4 years from now. Other super-super binary candidates include the quasar QSO B1312+7837 [period 6.4 years, est.masses (1-3)×10^8 solar], SDSSJ1430+2303 whose period in optical and X-rays decreased from about a year to a month in 3 years, suggesting merger before year 2026 [estimated masses (40-800)×10^6 solar], the blazar PKS 0346-27 [100-day period, mass of primary (9-60)×10^9 solar], SDSS J025214.67-002813.7 [4.6 cycles detected over 20 years of observation, summed mass $10^{8.4\pm0.1}$ solar with mass ratio 10], and PKS 1302-102 [period 1884±88 days, separation 0.1 parsec, masses $10^{8.3\text{-}9.4}$ solar]. This all suggests that (very roughly) 1 super-super merger occurs per month in the observable universe. LIGO detected ≈170 mergers of black holes during 2016-2023 whose individual masses ranged from 5 to 90 suns. The lifetime of the high power output stage of such mergers is linearly proportional to their mass, and was 0.1 second for the "GW170608" merger on 16 Nov. 2017 of 10.9+7.6 M_{sun} holes yielding 17.8 M_{sun} result. Hence the merger of two equal holes yielding a 10^9 M_{sun} result should output high power for 9 weeks.

④: *Non*quantum gravity (Newton or Einstein) is generated by *deterministic* masses, meaning ΔM≈0M. Therefore the gravity generated by any system with large *inherent* mass uncertainty (meaning ΔM of order M/1000 or more) can only be described by *quantum* gravity.

⑤: A similar scaling argument shows the duration of high power emission (meaning power exceeding any fixed positive constant times the peak power or Planck power) corresponds to a *constant* number of orbits, independent of m+M.

Other consequences of our model include $(t_{sing}-t)^{-5/4}$ behavior of the power curve at least for times t sufficiently before t_{merge}, where t_{merge} is the time of topological horizon-merger, and t_{sing} the later time at which the two point masses would in our model merge into one point, and to get this result we need to assume/pretend the spiral always is very near-circular; and (which partly justifies that) the automatic circularization of elliptical orbits.

Period(days)	**#moons**	**Eccentricities**
0-100	8	0-0.02
100-450	11	0.11-0.24
450-727	38	0.14-0.30
727-800	36	0.25-0.44

We first explain the **circularization**. If you were circularly orbiting the sun and wanted to convert to an elliptical orbit with the same energy, then (i) fire your rocket to "slow down", causing you to drop toward the sun on an elliptical orbit with perihelion located where you'd fired the rocket. Then (ii) when you reach aphelion, re-fire the rocket to "speed up" to regain your lost energy. Conversely, if in an elliptical orbit you want to circularize, then contrive to lose energy at aphelion and regain it at perihelion. This is exactly what our radiated-power formulas predict happen – maximum radiative losses occur at aphelion and minimum at perihelion – therefore orbits should automagically circularize as black holes inspiral. The same idea also should work for Jupiter's moons, except their energy losses are caused by tides (my point being that tides are strongest at aphelion) rather than gravitational wave emission. **Experimental confirmation:** the table of the 95 moons known by March 2023 shows the innermost have the least eccentricities, as expected since they experience the biggest tides. This table assumes Themisto's mean eccentricity≈0.25 [M.Brozovic & R.A.Jacobson: Astronomical J. 153,4 (2017) 147] and its third row omits the two "outlier" moons Carpo (period=456, eccent=0.416) and S/2003 J 18 (period=598, eccent=0.09) to make the trend clearer.

Now we explain the $(t_{sing}-t)^{-5/4}$ behavior. The Newtonian potential energy of two point masses M and m separated by distance L is E_{pot}=-GmM/L. The Newtonian kinetic energy $\Omega^2 I/2$ if they orbit their center of mass according to Kepler-Newton laws equals E_{kin}=(½)GmM/L. Therefore the total energy is $E=E_{kin}+E_{pot}$=(-½)GmM/L. By conservation of energy and Eddington's radiation-power formula $dE/dt=(-32/5)m^2M^2(m+M)L^{-5}G^4c^{-5}$ as we inspiral (approximating the spiral as a succession of circles infinitesimally radially-spaced). Hence $dE/dt=JE^5$ where for conciseness I have written $J=(1024/5)m^{-3}M^{-3}(m+M)G^{-1}c^{-5}$. The solution of this differential equation is $E=-2^{-1/2}J^{-1/4}(t_{sing}-t)^{-1/4}$, yielding the "**power curve**"

$$P_{binary}(t) = -dE/dt = 2^{-5}J^{-1/4}(t_{sing}-t)^{-5/4} = (5^{1/4}/32)\, m^{3/4}M^{3/4}(m+M)^{-1/4}\, G^{1/4}c^{5/4}\, (t_{sing}-t)^{-5/4}.$$

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