Test of the Weak Equivalence Principle for Neutrinos and Photons

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The observation of a neutrino burst within 3 h of the associated optical burst from supernova 1987A in the Large Magellanic Cloud provides a new test of the weak equivalence principle, by demonstrating that neutrinos and photons follow the same trajectories in the gravitational field of the galaxy. The accuracy of the test depends on the poorly known mass distribution in the outer parts of the galaxy, but is at least 0.5% and probably much better. This result provides direct evidence that the Shapiro geodesic time delay is identical, to this accuracy, for different elementary particles, independent of spin and internal quantum numbers.

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The observation of neutrinos from supernova 1987A[1,2] has provided many important new insights into the properties of neutrinos and the physics of supernovae. In this Letter we argue that it also yields a novel test of the weak equivalence principle (WEP).

For our purposes we take the WEP to state that any uncharged test body traveling in empty space will follow a trajectory independent of its internal structure and composition.[3] An alternative, somewhat stronger, statement is that space-time is endowed with a metric and the world lines of uncharged test bodies are geodesics of that metric.

There are a number of ways in which one might phrase the existence of possible violations of the WEP. For massive objects, one might suppose that the passive gravitational mass m_P is not equal to the inertial mass m_I. Alternatively, one might suppose that not all "freely falling" uncharged bodies follow geodesic trajectories. Such might be the case if there exist nonelectromagnetic long-range forces that couple to internal quantum numbers such as any combination of baryon or lepton number, or spin.

The most famous tests of the WEP are the Eötvös-type experiments,[3] which measure the acceleration of laboratory-sized objects made of different materials in a known gravitational field. In this way strong limits have been placed on the equivalence of various contributions to the inertial and passive gravitational masses of objects. Of particular relevance for our discussion is the limit of $\lesssim 1\%$ on the fractional difference of the weak-interaction contributions to passive versus inertial mass.[4]

The comparison of inertial and passive masses measures the accuracy of the WEP in a Newtonian context. Such a comparison is inappropriate for particles like photons or neutrinos, since their motion in a gravitational field is not correctly described by Newtonian dynamics. In this case an appropriate context is provided by the parametrized post-Newtonian (PPN) formalism.[3] Most theories of gravitation satisfying the WEP are encompassed by this formalism, and each theory is specified by a set of numerical coefficients (PPN parameters). The accuracy of the WEP may then by characterized by limits on the differences in PPN parameters for different species of particle.

For example, Shapiro[5] has pointed out that the time interval required for photons to traverse a given distance is longer in the presence of a gravitational potential $U(\mathbf{r})$ by

$$\Delta t = -\frac{1+\gamma}{c^2}\int_e^a U(\mathbf{r}(t))dt, \tag{1}$$

where e and a denote times of emission and absorption and γ is a PPN parameter. This result has been used to measure the parameter γ with use of radar ranging in the solar system and γ is found to be very nearly unity, consistent with the prediction of general relativity. To test the WEP, however, the issue is not the value of γ but whether it is the same for all species of particles, that is, whether, for example, the same time delay would be measured if neutrino radar rather than photon radar were used.

We suggest that the close coincidence in time of arrival of the photon and neutrino bursts from supernova 1987A provides a strong test of the WEP of precisely this kind.

The neutrino burst from SN1987A was detected at the Kamioka and IMB (Irvine-Michigan-Brookhaven) detectors on February 23.316 UT. Rapid optical brightening was first detected 1.0×10^4 s (less than 3 h) later, on February 23.443 UT.[6] This time delay is consistent with the time required for the shock wave from core collapse to propagate to the stellar surface for plausible models of

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the progenitor star.[7,8] Thus there is no evidence for any difference in propagation times of the neutrino and photon signals from the supernova to Earth. To be conservative we shall use an upper limit $\delta t = 10^4$ s on the difference in propagation times.

The principal uncertainty in the Shapiro time delay [Eq. (1)] is the unknown gravitational potential of the galaxy at large distances. We shall examine two simple models: (a) the Keplerian potential $U(r) = -GM/r$, where $M = 1.0 \times 10^{11} M_\odot$ is chosen to match the observed circular speed $v_c = 220$ km s^{-1} at the solar radius $r_\odot = 8.5$ kpc; (b) the isothermal potential $U(r) = v_c^2[\ln(r/r_{\max}) - 1]$ for $r < r_{\max}$, where the circular speed $v_c = 220$ km s^{-1} is assumed independent of radius and the potential is Keplerian for $r > r_{\max} = 100$ kpc. Case (a) assumes that most of the mass of the galaxy lies inside the solar radius and hence underestimates the time delay, while case (b) provides a plausible upper limit to the mass and extent of the galaxy and hence is likely to overestimate the delay. Neither model accounts properly for the disklike distribution of some of the galactic mass, but this should not have a strong influence on the result.

Using the known distance (≈ 52 kpc) and direction of the supernova, we find from Eq. (1) that the time delay due to the galactic potential is

$$\Delta t = \begin{cases} 1.3 \times 10^6 (1+\gamma) \text{ s for case (a)}, \\ 7.1 \times 10^6 (1+\gamma) \text{ s for case (b)}, \end{cases} \tag{2}$$

that is, one to six months for $\gamma \approx 1$. If then the WEP is violated, so that $1+\gamma$ is different for photons and neutrinos, the upper limit of 10^4 s on the difference in arrival times implies

$$\frac{\delta(1+\gamma)}{1+\gamma} < \begin{cases} 4 \times 10^{-3} \text{ for case (a)}, \\ 7 \times 10^{-4} \text{ for case (b)}, \end{cases} \tag{3}$$

where we have assumed $\gamma \approx 1$.

These results remain valid if the neutrino has a small nonzero rest mass m_0, so long as $\gamma_r = E/m_0c^2$ satisfies $\gamma_r^2 |U|/c^2 \gg 1$ so that the special-relativistic time delay is much less than the Shapiro time delay. Since $|U|/c^2 \approx 10^{-6}$ but $\gamma_r^2 \gtrsim 10^{12}$ [the measured neutrino energies exceed ~ 10 MeV, and dispersion arguments for the neutrino signal limit the mass to be less than ~ 10 eV (see, for example, Bahcall and Glashow[9] and Kolb, Stebbins, and Turner[10])], this inequality is easily satisfied.

Thus the coincidence in timing of the neutrino and photon bursts from SN1987A verifies the WEP for neutrinos and photons to better than 0.5% accuracy. This accuracy is based on a very conservative estimate of the uncertainty in the time difference between core collapse and the optical brightening of the supernova, and may be substantially reduced as our understanding of the supernova grows. This is the first direct verification of the WEP for relativistic particles, and provides the most stringent test of the WEP for mass-energy due to weak interactions.

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