Space-Based Measurement of the Neutron Lifetime using Data from the Neutron Spectrometer on NASA's MESSENGER Mission

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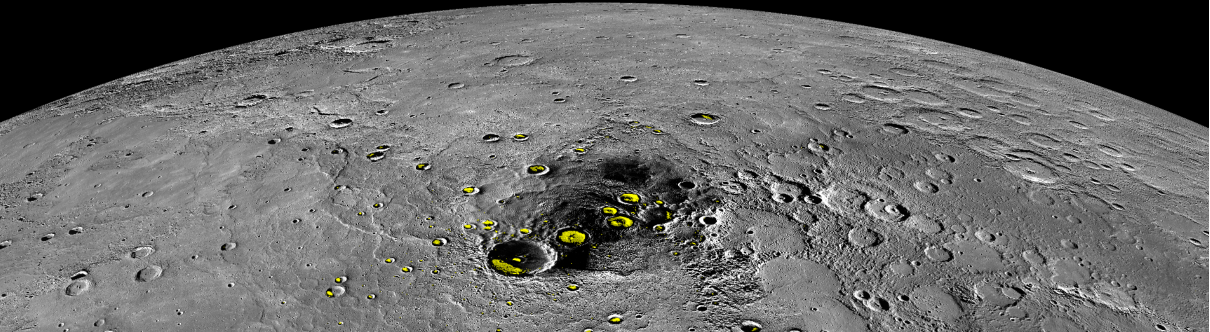
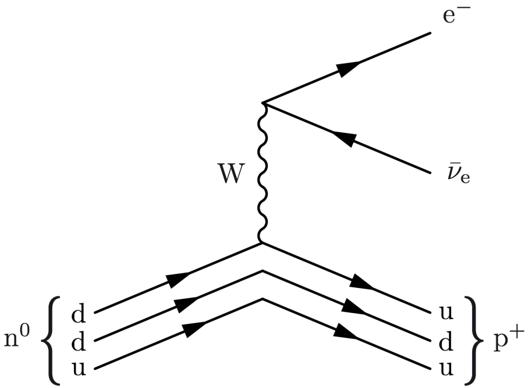


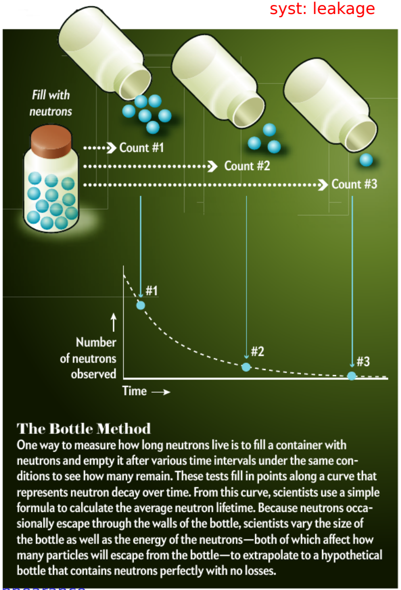
τ_n – Why Bother?

- electro-weak physics of β decay (CKM matrix element V_{ud})
- big-bang nucleosynthesis
  $n + e^+ \leftrightarrow p + \bar{\nu}_e$
  $n + \nu_e \leftrightarrow p + e^-$
  $n \to p + e^- + \bar{\nu}_e$
  (n/p $\sim$ 1/6 at freeze-out, eventually $\sim$ 1/7)
- solar pp chain (β^+ decay)
  $p + p \to {}^2H + e^+ + \nu_e$
- neutron stars (inverse β^- decay)
  $p + e^- \to n + \nu_e$



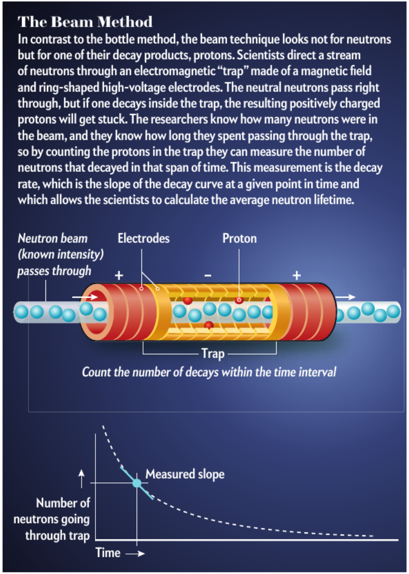
Standard τ_n Measurement

syst: leakage



n-disappearance

syst: beam intensity, proton detection efficieny



p-appearance

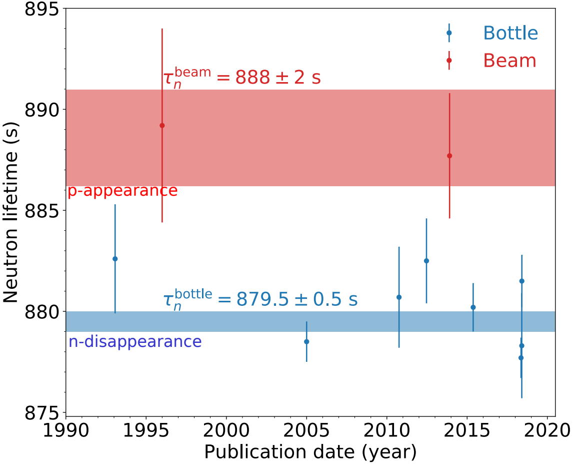
n -> X + X ???


PARTICLE PHYSICS

the neutron enigma

Two precision experiments disagree on how long neutrons live before decaying. Does the discrepancy reflect measurement errors or point to some deeper mystery?

By Geoffrey L. Greene and Peter Geltenbort



4.1 sigma difference!

τ_n in Space (original idea)

Nuclear Instruments and Methods in Physics Research A287 (1990) 595–605
North-Holland

A TECHNIQUE TO MEASURE THE NEUTRON LIFETIME FROM LOW-EARTH ORBIT

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A new technique to measure the mean life of the neutron to beta decay, τ_n, is described. It uses the fact that neutrons created in the atmosphere with energies below 0.65 eV are gravitationally bound. Consequently, in the absence of beta decay, upward- and downward-going neutron currents above the atmosphere would be equal. The actual ratio of these currents therefore provides a sensitive measure of τ_n. An estimate of up–down countrates, of all known backgrounds, and of systematic uncertainties for a conceptual experiment indicates that an accuracy on τ_n of better than 1% could be achieved using a properly designed sensor in low-Earth orbit.

τ_n in Space (original idea)

The ability to make a space-based measurement of τ_n is made possible by the fact that planetary atmospheres and—for airless bodies—solid surfaces are constantly bombarded by galactic cosmic rays (GCRs). These energetic particles, which are mostly high-energy protons, collide with atomic nuclei leading to spallation reactions in which large numbers of high-energy neutrons are produced. These neutrons undergo further collisions with nuclei and have their energy moderated downwards. A fraction of the neutrons undergo a sufficiently large number of collisions that they reach thermal equilibrium with the atmosphere or solid surface.

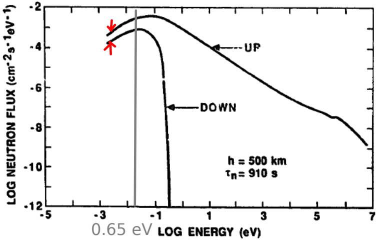


Fig. 2. Calculated up-going and down-going neutron currents at an altitude $h = R - R_0 = 500$ km using the gravitationally augmented ONEDANT computer code.

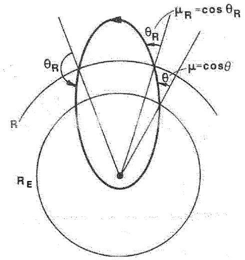
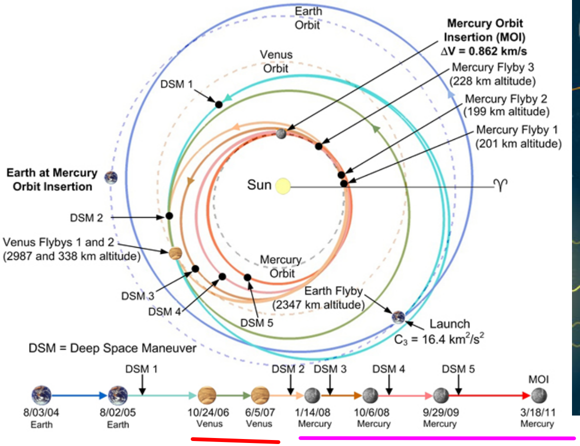


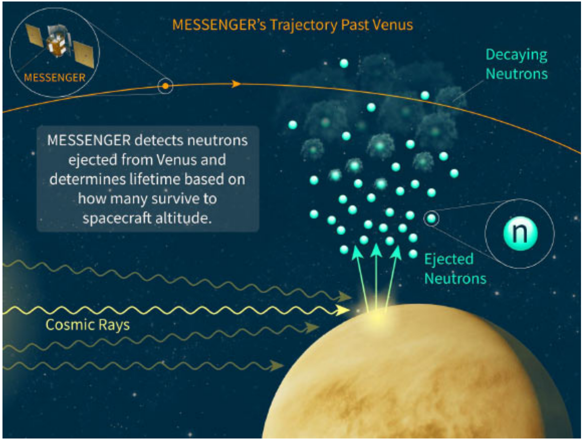
Figure 2: Orbit of a gravitationally bound neutron about the Earth. (Adapted from [30].) R is the radius of the satellite's orbit about the Earth. R_E is the radius to the top of the Earth's atmosphere. θ is the angle of of the neutron's elliptical orbit (with focal point at the center of the Earth) with respect to the normal at the Earth's surface. θ_R is the similar angle with respect to the satellite's orbit.

The fundamental idea of this experiment was described in Ref. [29]. (In Figure 2 we show the geometry of the system.) It depends on the fact that the neutrons created in Earth's atmosphere by cosmic rays, and leaving the atmosphere with kinetic energies, $K(R_E)$, below 0.65 eV, are gravitationally bound [30]. Further, of these, some survive going upward to $h = 500$ km altitude, or orbital altitude $r = R \equiv h + R_E$. They now have $K(R) < 0.606$ eV, and are still gravitationally bound. After having passed this particular orbital altitude on the way up, some of these neutrons will have decayed by the time they fall back down to the same altitude. Therefore, if one has neutron detectors in a circular Earth orbit, the difference between the energy spectra of up-going and down-going neutrons with energies below 0.606 eV is a measure of the neutron lifetime. !!

The round-trip time for an up-going neutron, with a kinetic energy of a few tenths of an eV, is of the order of the neutron lifetime. (See Fig. 3.)

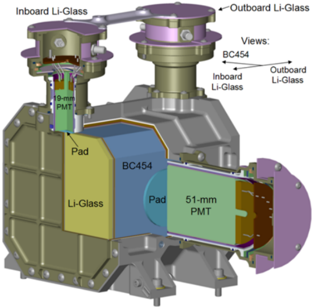
τ_n in Space with NASA's Messenger

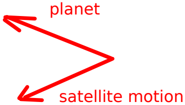




Messenger's Neutron Detector

Fig. 6 CAD model cutaway view of NS sensor. The housing is cut open to show the internal scintillator and PMT arrangements. The intended view is given for each scintillator. The direction given for BC454 is nadir, towards the planet





Here, we make use of data taken by NASA's MESSENGER spacecraft to demonstrate the feasibility of space-based measurement of τ_n. The MESSENGER neutron spectrometer (NS) was designed to measure Mercury's surface composition with special emphasis placed on testing the hypothesis that the radar bright regions at Mercury's poles are a consequence of the presence of water-ice in the permanently shadowed craters [20]. MESSENGER's neutron detector consisted of a 10^3 cm^3 cube of borated plastic scintillator sandwiched between two 4 mm thick, 100 cm^2 Li-glass plates [18]. These Li-glass detectors were sensitive to neutrons with energies in the thermal regime, via the neutron capture reaction $^6\text{Li} + n \rightarrow {}^3\text{H} + {}^4\text{He}$,

During the flybys, each Li-glass detector recorded a 64-channel energy-deposition spectrum every two seconds. On the ground, these two-second spectra were combined into 20-second spectra for a total of 133 20-second observations at Venus and 78 at Mercury. The measured spectra include the 4.78 MeV energy deposition peak from the $^6\text{Li}(n,\alpha)^3\text{H}$ neutron-capture reaction, which is the primary signal of interest, as well as a continuum background due to the interaction of GCRs and high-energy, planet-originating neutrons with the spacecraft and detector [21].

Data Analysis

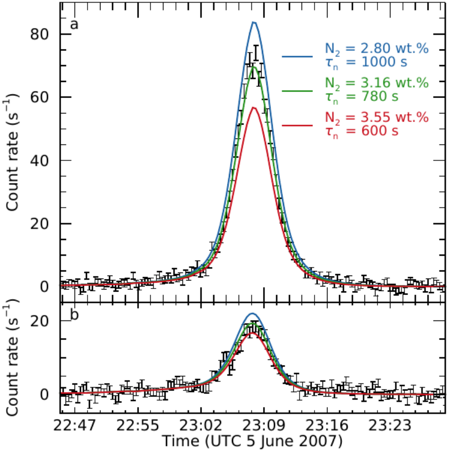


FIG. 2. Modeled and measured data taken by MESSENGER's Neutron Spectrometer when the spacecraft was within 10^4 km of Venus' surface for the Li-glass detectors with their surface normals approximately (a) aligned with and (b) opposite the direction of spacecraft motion.

In our new approach τ_n is determined by comparing the output of a set of models based on different lifetimes to the data measured at Mercury and Venus. τ_n, along with surface or atmospheric composition and the planet's mass, determines the rate at which the neutron flux decreases with increasing distance from the planets.

The composition of Venus' atmosphere, from where detected neutrons originate, is both simple and relatively uniform. The atmosphere is principally comprised of only two components: CO_2 makes up approximately 96% by volume with the remaining part composed almost entirely of N_2 [23]. Since nitrogen is an effective neutron absorber via the $^{14}N + n \rightarrow {}^{15}N$ and $^{14}N + n \rightarrow {}^{14}C + p$ reactions, its abundance has a strong effect on the Venus-originating thermal neutron flux [24] that we use to measure τ_n. Venus' homopause is at 120 km [25], which is above the altitude at which the thermal neutrons originate (60–80 km [26]). Beneath the homopause the atmosphere is uniform as different species are homogeneously mixed by eddy diffusion and turbulent mixing (though recent evidence implies the existence of a discontinuity at an altitude of 50 km [26]). As the neutron flux is originating beneath the homopause we can consider Venus' atmosphere to be compositionally uniform. Atmospheric temperature is also important as the detected thermal neutrons are in thermal equilibrium with the atmosphere, and so have their energy distribution determined by its temperature. The temperature, at the altitudes from which neutrons are sourced, varies little over time with

Data Analysis

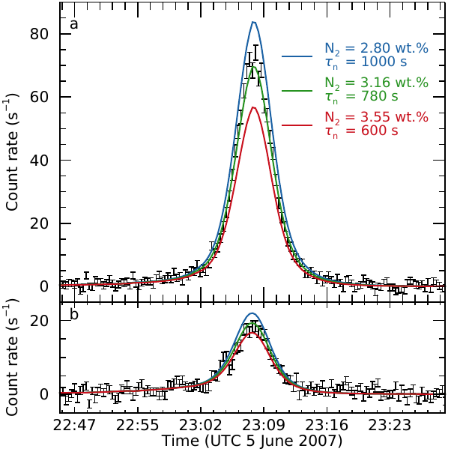


FIG. 2. Modeled and measured data taken by MESSENGER's Neutron Spectrometer when the spacecraft was within 10^4 km of Venus' surface for the Li-glass detectors with their surface normals approximately (a) aligned with and (b) opposite the direction of spacecraft motion.

large variations not seen beneath 100 km [27]. Latitudinal variation in temperature is not seen between 30° S and 30° N [28], where the closest approach of the flyby took place, and is less than 30% globally. For the Venus flyby a set of models with different neutron lifetimes and atmospheric N_2 abundances were generated.

In addition to Venus' atmospheric uniformity, the planet's relatively large mass is advantageous when measuring τ_n. Thermal neutrons have an energy less than 1 eV. Since Venus' gravitational binding energy is 0.56 eV, τ_n has a substantial effect on the neutron flux at all altitudes where a thermal neutron flux is detectable. The basis of this measurement technique is a comparison of the measured Li-glass-derived data with models of the count rate constructed assuming different values of τ_n.

The final step in the modeling process was setting the absolute normalization of the models. Normalization is required as our models of neutron production account for the GCR spectral shape but not for the absolute particle fluence. Ideally, the normalization would be set using the data at Venus to avoid the systematics associated with the measurements taken at Mercury. However, for the 45 minutes of data that are available the statistics prevent this. If the normalization is determined from the Venus data then the set of models with different parameters tend to overlap and although the shapes of the curves differ the statistics are not sufficient to distinguish between them.

Result

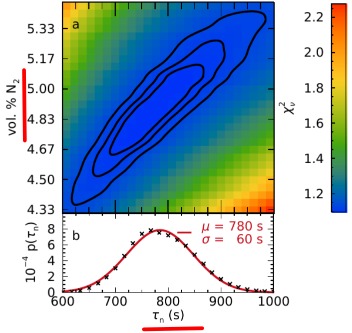


FIG. 3. (a) χ^2 comparison of the models with differing τ_n values and N_2 abundances. The contours show the 68, 95, and 99 % confidence intervals, which were calculated assuming a Gaussian likelihood. (b) The probability distribution of τ_n using the likelihoods derived from (a). The red curve is a Gaussian fit to the points, with the fit parameters shown.

Converting the χ^2 values to likelihoods and integrating to marginalize out N_2 abundance enables the probability distribution of τ_n to be calculated in Fig. 3(b). This calculation implies $\tau_n = 780 \pm 60_{\text{stat}}$ s, which is a 1.6σ difference from the PDG value of 880.2 ± 1.0 s. The result demonstrates the feasibility of measuring τ_n using a space-based experiment.

TABLE I. Summary of systematic uncertainties associated with the measurement of τ_n based on comparing models to data taken at Venus and Mercury. Those that affect only this particular implementation of the neutron lifetime measurement are quantified.

Source of uncertainty	Uncertainty (s)
Mercury's surface composition	±70
Change in the GCR environment	±20
Instrument response function	
Variation in Venus' atmosphere with time of day	
Variation in Venus' atmosphere with latitude	
Species other than CO_2 and N_2 in Venus' atmosphere	
Uncertainties in the Monte Carlo modeling	

only this paper

space in general

It is clear from the preceding uncertainty estimates that using data taken at Mercury to provide the model normalization introduces a model-dependence that is absent from the original, optimized form of a space-based measurement. This compromise is a consequence of the fact that this mission was not designed with the goal of measuring τ_n but of answering several other questions in planetary science. However, the success of a measurement using this suboptimal dataset demonstrates the feasibility of measuring τ_n from space and provides an initial step on the path to flying an optimized mission. These systematics could be avoided if more data were taken at Venus, because improving the statistics of the Venus measurements would enable that data set to be used alone. The measurement of τ_n would then not be set by the mean count rate in the models but only by how the detected neutron count rate changes with altitude.

Conclusions

V. CONCLUSIONS

Using data taken by MESSENGER's Neutron Spectrometer during its flybys of Venus and Mercury we found $\tau_n = 780 \pm 60_{\mathrm{stat}} \pm 70_{\mathrm{syst}}$ s. This result establishes the feasibility of making a measurement of τ_n from space. The statistical uncertainties are large due to the short duration of the flybys (totaling 70 minutes with altitude below 10^4 km) and subsequent small amount of data taken, which is a consequence of the mission not being planned with this measurement in mind. The systematic errors are similarly large; however, the worst of these could be avoided with a longer duration experiment using observations taken only at Venus thus avoiding the systematics associated with uncertainties in Mercury's surface composition. The reduction of smaller-magnitude systematics to the 1 s level required to potentially resolve the neutron lifetime anomaly requires a detailed mission design study that builds on the result of this paper.