Astronomers confirm fundamental relationship in atomic physics

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A team of astronomers has used the pattern of light coming from distant methanol molecules to determine that the ratio of the mass of the proton to the mass of the electron has changed by no more than one part in ten million in the last seven billion years.

Put another way, it has now been measured that a critical aspect of the physics underlying molecular and atomic matter has changed by a maximum of one hundred thousandth of a percent for at least the second half of the lifetime of the universe, and most likely has not changed at all.

As detailed in the report published in the December 13, 2012 issue of *Science*, the experimenters used spectroscopy, the study of the character of light from a particular source, to analyze light absorbed by methanol molecules in a distant galaxy seven billion light years from Earth to measure the possible variation of the proton-electron mass ratio over the course of the time taken for the light to reach Earth.

The masses of the proton and electron, and all atomic and subatomic particles, are not values intrinsic to the theory that describes their interactions, the Standard Model of particle physics. Rather, the mass of each particle is an experimentally measured quantity. Every experiment to date has shown, to an extremely high degree of accuracy, that each elementary particle has the same mass as every other of its kind.

Studying the proton-electron mass ratio also gives insight into the relationship between the electromagnetic, weak nuclear and strong nuclear forces and whether or not these three of the four fundamental forces of the universe change over time.

The results of the experiment agree with Einstein's Equivalence Principle, a basic assumption of General Relativity, which postulates that the laws of physics—including particle masses as well as other constants which determine the strength of interactions between fundamental particles—are constant throughout space and time.

As Karl Menten, the director of the Max Planck Institute involved in the research, noted: “If you see any variations in that fundamental constant, then you would know that something was wrong in our understanding of the foundation of physics.”

The data are also evidence against experiments that suggest that the fine structure constant, another fundamental constant which mediates electromagnetic interactions, changes through space or time.

The recent experiment was the outcome of international collaboration, involving physicists from the VU University of Amsterdam, the Max Planck Institute of Germany and the King Abdulaziz University in Saudi Arabia. In the course of 2011 and 2012, the team used the Effelsberg 100-meter radio telescope, located in north Germany, to make precise measurements of light passing through methanol molecules in the PKS1830-211 galaxy, seven billion light years from Earth.

The team analyzed four radio frequencies that methanol absorbs and compared these against the compound’s known absorption spectrum.

As explained by quantum mechanics, each photon carries a discrete packet of energy related to the light’s frequency. A molecule absorbs a photon as it *shifts* to a more excited, or higher, energy level. As with photon energies, a molecule’s energy levels are quantised and can only take discrete values, meaning that the molecule will accept only specific packets of energy, and hence only photons of light of a particular frequency. This results in the observed discrete lines formed on the molecules’ absorption spectrum.

Any difference in the values of the four measured frequencies would mean the methanol molecules were absorbing different amounts of energy, which physicists can use to calculate a change in the relative masses of the protons and electrons. The physicists were forced to allow in their calculations for the fact that, because PKS1830-211 is moving away from the Earth, light from the galaxy is red shifted—meaning that from the Earth's reference frame the light has a longer wavelength, or is closer to the red end of the electromagnetic spectrum.

The team chose to analyze methanol in particular both because of its abundance throughout the universe as well as the sensitivity of its energy levels, due to the structure of the molecule, to any change in the proton-electron mass ratio.

Methanol (CH3OH), consists of a methyl group attached to an OH group. The different, quantised, energy levels of the molecule depend on both the rotation of the molecule as a whole, as well as the internal torsion of the OH group relative to the methyl (CH3) group.

Two of the four frequencies analysed by the astronomers corresponded to energy transitions involving changes in the rotation of the whole molecule. These transitions are inversely proportional to the change of the proton-electron mass ratio—giving them a "sensitivity factor" of -1.

However, the transitions involving both the rotation of the whole molecule and an internal rotation of the OH group are far more sensitive to a change in the mass ratio. The other two frequencies observed by the team, corresponding to such energy changes, had sensitivities of -7.4 and -32.8. This made possible the extremely narrow limit placed on potential variation of the mass ratio.

In fact, due to the electric repulsion of the charged hydrogen nuclei in the CH3 group, the internal rotation of the OH group would not be possible under the laws of classical physics. It is only allowed by a quantum mechanical effect called quantum tunnelling, which makes it possible for the OH group to rotate and pass through the "energy barrier" caused by the repulsion of the other hydrogen atoms.

In addition to the team that conducted the experiment, many other physicists internationally contributed to the theoretical and experimental work leading up to it and making it possible. This included the calculation of the sensitivities of the various energy transitions within methanol.

In the past decade in particular, experimental research in the possible variation of the relative masses of the proton and electron over cosmological scales has been made more attractive due to the development of technology. A number of teams, using ammonia and hydrogen as well as methanol, have measured change in the proton-electron mass ratio, but the recent experiment has been able to place by far the most stringent limit on such a variation. Due to their structure, ammonia and hydrogen do not have high sensitivity factors resulting from internal rotations.