A tale of two masses

The most precise measurements of the atomic masses of the proton and the electron make use of Penning traps, and for the latter, a hydrogen-like ion, as **Edmund Myers** explains.

In the late 1890s, J. J. Thomson (pictured) demonstrated that cathode rays were composed of charged particles. By deflecting them using magnetic fields, he found that their mass-to-charge ratio was nearly 2,000 times smaller than that of the lightest ion, that of hydrogen. Nowadays, the atomic mass of the electron — the mass relative to a ^{12}C atom — and the electron-to-proton mass ratio m_e/m_p are important fundamental constants. From these, many other physical quantities are derived, so ever more precise values are required.

While further developments using magnetically deflected beams of charged particles opened the field of mass spectrometry and produced better values for m_e/m_p, it was the application of the Penning trap in the 1970s that first yielded results with better than 1 part-per-million precision[1]. In a Penning trap, charged particles are trapped, in ultra-high vacuum, by the combination of a uniform magnetic field and a quadrupolar electric field. The motions of the particles are then harmonic; their frequencies are independent of amplitude. Moreover, the 'true' cyclotron frequency — the frequency of the circular motion that a charged particle would have in a magnetic field without an electric field, proportional to its charge-to-mass ratio q/m — can be precisely calculated from the measurable motional frequencies[2]. Hence, by measuring the motional frequencies of an electron (or proton) and, subsequently, of a carbon ion trapped in the same magnetic field, their mass ratio can be accurately obtained.

Improvements in Penning trap techniques, particularly the development of the cryogenic Penning trap, with non-destructive detection of particle motion through currents induced in the trap electrodes, enabled cyclotron-frequency measurements on a single charged particle trapped for many days. In the 1990s, this led to a proton mass measurement with better than 1 part-per-billion (ppb) precision[3], and what is still the most precise direct measurement of the mass of the electron, with an uncertainty around 2 ppb (ref. 4).

Although by 2001 the uncertainty in the atomic mass for the proton was further reduced to the 0.1 ppb level[5] — the 2014 CODATA value of 1.007,276,466,879 u, with an uncertainty of 9×10^{-11} u, is mainly based on this result — achieving a similar improvement for the electron was stymied by two sources of systematic error. First, because of its low mass, an electron in a Penning trap, even at 4.2 K, has a thermal energy sufficient to shift its mass relativistically by 0.7 ppb. Second, the electron's cyclotron motion, the frequency of which is in the microwave region, is perturbed by interaction with the cavity modes of the trap electrodes in which it is confined.

As a way around these obstacles, a group of physicists at the University of Mainz, the Max Planck Institute for Nuclear Physics in Heidelberg and the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt has developed an indirect Penning trap approach that uses the one-electron ion $^{12}C^{5+}$. The essence of the method is that, for an electron (a structureless particle), the magnetic moment is fundamentally related to its charge-to-mass ratio, as was originally shown by Paul Dirac. In a Penning trap, the electron's magnetic moment interacts with the magnetic field B and splits the ground level of the C^{5+} ion into two Zeeman states, separated by an energy $\hbar\omega_s = Bg(e\hbar/2m_e)$, where $\hbar$ is the reduced Planck constant and e the elementary charge. To lowest order, the dimensionless g-factor has the Dirac value of 2, but its value for the electron in C^{5+} is modified by relativistic and quantum electrodynamic effects. Thanks to continued progress in quantum electrodynamic theory and improved determinations of the fine-structure constant, the g-factor of C^{5+} can now be calculated with an uncertainty of only a few parts in 10^{12}. By measuring ω_s, the frequency of microwave radiation that flips the bound electron's spin, and the ion's cyclotron frequency $\omega_c = Bq/m_{ion}$ (q and m_{ion} are the C^{5+} ion's charge and mass, respectively), the magnetic field can be cancelled out. What is left is the mass of the electron relative to that of the carbon ion: $m_e/m_{ion} = (g/2)(e/q)(\omega_c/\omega_s)$. Since the C^{5+} ion is much heavier than the electron, its cyclotron frequency is in the radio- rather than the microwave region, and is subject to much smaller relativistic and cavity shifts than that of a free electron. And, since the two frequencies can be measured simultaneously, their ratio is insensitive to drifts in the magnetic field, enabling results with very high precision.

The group has now measured ω_c/ω_s of C^{5+} to 0.03 ppb, yielding a similarly precise value for the electron's atomic mass, m_e = 0.000,548,579,909,070 u, with an uncertainty of 1.6×10^{-14} u (ref. 6). So, currently, an improved m_e/m_p value awaits new measurements on the proton. ❐

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m e Å s u R E_h F Ω R_∞ μ_0 ε_0 α σ V R e

Correction

In the Measure for Measure 'A tale of two masses' (*Nature Physics* **12,** 986; 2016), one of the affiliations of the group of physicists that developed a Penning trap approach was incorrect and should have read 'Max Planck Institute for Nuclear Physics in Heidelberg'. This has now been corrected online after print 21 October 2016.