

Measurement of the mass difference between tritium and helium-3 ions by a high-resolution ion-cyclotron-resonance method

É. T. Lippmaa, R. Ī. Pikver, É. R. Suurmaa, Ya. O. Past, Yu. Kh. Puskar, I. A. Koppel', and A. A. Tammik

Institute of Chemical and Biological Physics, Academy of Sciences of the USSR

(Submitted 29 April 1984)

Pis'ma Zh. Eksp. Teor. Fiz. **39**, No. 11, 529–531 (10 June 1984)

The mass difference between tritium and helium-3 ions has been found to be $18\,588 \pm 3$ eV by a high-resolution ion-cyclotron-resonance method in a strong field (4.7 T).

In 1980, Lyubimov *et al.*^{1,2} showed that the electron antineutrino may have a nonzero rest mass roughly in the range $14 \leq M_\nu \leq 46$ eV. The possible existence of a nonzero neutrino mass is one of the foremost problems of the physics of elementary particles and cosmology today.³ A determination of the rest mass of the electron antineutrino from the end-point energy of the tritium β spectrum requires very accurate independent measurements of the mass difference between the initial and final atoms involved in the β decay. This mass difference differs from the corresponding

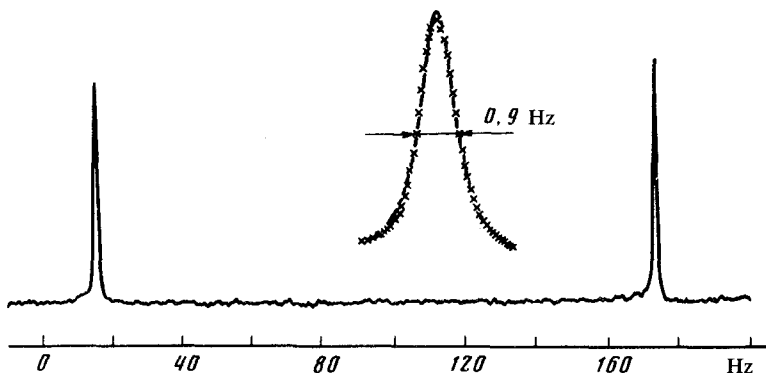


FIG. 1. Ion-cyclotron-resonance spectrum (built up in 80 pulses) of a mixture of helium-3 and tritium. The line width at half-maximum is 0.9 Hz. The broadening due to the filtering of the signal is 0.5 Hz. Solid curve—theoretical approximation by a Lorentzian curve; points—experimental results.

mass difference of the ions by the difference between the first ionization potentials of the helium and tritium atoms (10.9828 eV).

Measurements of the ${}^3\text{T}-{}^3\text{He}$ atomic mass difference have been reported in several papers,^{4,5} but there has been a significant scatter in the results. The best mass-spectroscopic resolution (4×10^5) was achieved by Smith.⁶ A recently developed ion-cyclotron-resonance method with pulsed signal excitation and the subsequent use of Fourier transforms has opened the way to a substantial improvement in the resolution of mass spectrometry, to a level of 10^7 or better.⁷ The first ion-cyclotron-resonance spectrometer, constructed in 1980 at the Institute of Chemical and Biological Physics,⁸ provided a resolution up to 10^5 . A new version, which uses a Bruker (West Germany) SXP-200 NMR spectrometer with a superconducting magnet and a highly uniform magnetic field (4.7 T; the diameter of the thermal aperture is 89 mm), has an ion-cyclotron resolution up to 6×10^7 (the smallest line width is 0.3 Hz at the frequency 24 MHz). At this resolution, the resonant frequencies of the ${}^3\text{He}$ and ${}^3\text{T}$ ions can be measured within 0.001 Hz through a numerical approximation of the measured lines by Lorentzian lines on the computer of the spectrometer.

The high-vacuum system of the spectrometer has NORD-100 and VacIon magnetodischarge pumps (30 liter/s) and provides a vacuum down to 2×10^{-9} Torr. The gold-plated measuring cell, with dimensions of $33 \times 33 \times 40$ mm, is positioned at the center of a solenoid in a uniform magnetic field. After the ions are produced in the cell by electron impact (from 22 to 100 V and from 0.5 to 100 ms), all the ions except ${}^3\text{He}^+$ and ${}^3\text{T}^+$ are removed by an rf axial-excitation pulse which is scanned from 10 to 150 kHz. The ions of interest are then excited by an rf pulse into orbits less than 3 mm in radius. The free-precession signal induced in the side plates is built up (over 10–100 pulses) in the memory of an Aspect 2000 computer. The peak frequencies are determined after Fourier transforms are taken through a numerical approximation by a Lorentzian curve. The mass difference between the ions is calculated from

$$m_{\text{}^3\text{T}^+} - m_{\text{}^3\text{He}^+} = \frac{m_{\text{}^3\text{T}^+}}{f_{\text{}^3\text{He}^+}} (f_{\text{}^3\text{He}^+} - f_{\text{}^3\text{T}^+}),$$

where $f_{\text{}^3\text{He}^+} = 23.935\,988$ MHz, $f_{\text{}^3\text{T}^+} = 23.935\,830$ MHz, and $m_{\text{}^3\text{T}^+} = 2.808\,9192$ GeV.

The relativistic correction and the correction for the axial motion of the ions at a retarding voltage of 2 V is ~ 130 Hz, which leads to an error of less than 0.1 eV in the ion mass difference.

The maximum scatter in the measured frequency difference $f_{\text{}^3\text{He}^+} - f_{\text{}^3\text{T}^+}$ ranges from 158.22 to 158.55 Hz in experiments in which the line width is 1.5 ± 0.5 Hz, and the ratio of the peak values of the lines ($\text{}^3\text{He}^+/\text{}^3\text{T}^+$) lies between 0.7 and 2.0. Working from a statistical Gaussian distribution, we find an average frequency difference $f_{\text{}^3\text{He}^+} - f_{\text{}^3\text{T}^+} = 158.39 \pm 0.03$ Hz, from which we find a mass difference of $18\,588 \pm 3$ eV or a mass difference of $18\,599 \pm 3$ eV between the atoms.

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Translated by Dave Parsons

Edited by S. J. Amoretti