学位論文 (要約)

Direct Measurement of the Hyperfine Structure Interval of Positronium Using High Power Millimeter Wave Technology

(大強度ミリ波技術を用いたポジトロニウム超微細構造の直接測定)

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DIRECT MEASUREMENT OF THE HYPERFINE STRUCTURE INTERVAL OF POSITRONIUM USING HIGH POWER MILLIMETER WAVE TECHNOLOGY

PH. D. THESIS

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Abstract

In this thesis, positronium hyperfine structure (Ps-HFS) is directly measured. This is the first direct measurement of Ps-HFS. Although Ps-HFS has been *indirectly* measured with a Zeeman splitting method since 1952, there is no precedents for the *direct* measurement because Ps-HFS is in the millimeter-wave range (frequency $\Delta_{\mathrm{Ps}}^{\mathrm{HFS}} = 203$ GHz, wavelength $= 1.5$ mm, energy difference $= 0.83$ meV). A gyrotron oscillator is developed as a high-power millimeter-wave radiation source. A Fabry-Pérot resonant cavity accumulates radiation to equivalent power of about 20 kW to cause the induced transition between *ortho*-positronium and *para*-positronium. The obtained Ps-HFS value is

$$\Delta_{\mathrm{Ps}}^{\mathrm{HFS}} = 203.39^{+0.15}_{-0.14}\,(\mathrm{stat.}) \pm 0.11\,(\mathrm{syst.})\,\mathrm{GHz} \tag{1}$$

At the same time, lifetime of *para*-positronium is directly measured as

$$\tau_{\mathrm{p\text{-}Ps}} = 89^{+18}_{-15}\,(\mathrm{stat.}) \pm 10\,(\mathrm{syst.})\,\mathrm{ps} \tag{2}$$

This is also the first direct measurement of $\tau_{\mathrm{p\text{-}Ps}}$. They are consistent with QED calculations.

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Chapter 1

Introduction

インターネット公表に関する共著者全員の同意が得られていないため, 本章については非公開.

Chapter 2

Experiment

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Chapter 3

Analysis

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Chapter 4

Discussion

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Chapter 5

Conclusion

Ps-HFS was firstly measured with a direct transition method. Measurement of the Ps-HFS is difficult because the Ps-HFS transition is suppressed with finite lifetime of Ps, and Ps-HFS is in the millimeter-wave region. It requires development of a high-power millimeter-wave system, which is a big challenge for current technology of plasma physics and millimeter-wave optics.

A gyrotron oscillator was developed as a high-power (> 100 W) millimeter-wave radiation source. It was a technical challenge to fabricate and control the gyrotron with such high frequency (203 GHz). We changed output frequency of the gyrotron by replacing an internal RF cavity. A long time (more than a week) operations were the first trial with the high-power gyrotron.

A Fabry-Pérot resonant cavity accumulates radiation to equivalent power of about 20 kW to cause the induced transition from *o*-Ps to *p*-Ps. In the millimeter-wave range, a great effort was required to design a half mirror with high reflectivity, low loss, and withstanding against high-power dumping. A gold mesh mirror on a silicon substrate was developed.

There are no established methods to measure high-power millimeter-wave radiation today. Accumulated power is, especially, difficult to estimate because cavity finesse (Q-factor) and coupling cannot be measured with rather wide line-width of gyrotron output. This thesis reported a new way to directly measure the accumulated power. We calibrated output of the pyroelectric detector with temperature increase of a water load. We corrected reflected-beam effects which reduced the oscillation efficiency of the gyrotron.

Output power from the gyrotron was stabilized with a feed-back control of the electron-beam current. Accumulated power wan the Fabry-Pérot cavity is also stabilized by controlling length of the cavity. There are inevitable fluctuations in this accumulated power in one pulse because of line-width and drift of the gyrotron frequency. We corrected this effect with a Monte Carlo simulation in analysis.

A Ps formation assembly and γ-ray detectors were carefully arranged to enhance S/N of the direct transition. Use of neopentane gas was a key to reduce an increase of Ps formation probability due to positron acceleration by millimeter-wave radiation. $LaBr_3(Ce)$ scintillators are used to detect γ rays with high energy resolution.

The reaction cross-section of the Ps-HFS transition is studied using MC, and obtained Ps-HFS value $\Delta_{\mathrm{Ps}}^{\mathrm{HFS}}$, lifetime of p-Ps $\tau_{\mathrm{p-Ps}}$, and the Einstein A coefficient are

$$\Delta_{\mathrm{Ps}}^{\mathrm{HFS}} = 203.39^{+0.15}_{-0.14}\,(\mathrm{stat.}) \pm 0.11\,(\mathrm{syst.})\,\mathrm{GHz} \tag{5.1}$$

$$\tau_{\mathrm{p-Ps}} = 89^{+18}_{-15}\,(\mathrm{stat.}) \pm 10\,(\mathrm{syst.})\,\mathrm{ps} \tag{5.2}$$

$$A = 3.69 \pm 0.48\,(\mathrm{stat.}) \pm 0.29\,(\mathrm{syst.}) \times 10^{-8}\,\mathrm{s}^{-1}. \tag{5.3}$$

This is the first direct measurement of Ps-HFS and lifetime of p-Ps. These are consistent with the QED calculations.

Precise but indirect measurements of Ps-HFS were performed in 1970's and 1980's. Recent QED calculations of Ps-HFS differ from the measured value by 3.04(79) MHz (15 ppm), which is unlikely to be due to a statistical fluctuation (3.9 standard deviations). A candidate in the future to test this discrepancy is the direct measurement of Ps-HFS firstly performed in this thesis. Some technical improvements are needed to reach a sufficient level of precision to address the observed discrepancy. This thesis pointed out development of a frequency tunable gyrotron of 100 kW and a method of efficient Ps production in vacuum with a positron beam.

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Appendix A

Gyrotron Theory

インターネット公表に関する共著者全員の同意が得られていないため, 本章については非公開.

Appendix B

Theory of Positron Acceleration

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Appendix C

Data Summary

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Appendix D

Small Systematic Uncertainties

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