PHYSICAL REVIEW A VOLUME 49, NUMBER 3 MARCH 1994

Precision measurement of the isotope shift of the $2\,^3S_1-3\,^3P_0$ transition in helium

F. Marin,* F. Minardi,* F. S. Pavone, and M. Inguscio
Dipartimento di Fisica and European Laboratory for Nonlinear Spectroscopy (LENS), Università di Firenze, Largo E. Fermi 2, 50125 Firenze, Italy
(Received 11 October 1993)

A heterodyne spectroscopic scheme, using only one laser tuned to the atomic wavelength, is applied to the measurement of the ^{3}He($F=\frac{1}{2}$-$\frac{1}{2}$ component)-^{4}He separation for the $2\,^3S_1-3\,^3P_0$ transition at 389 nm. The experimental result is 45 394 425(137) kHz and the isotope shift deduced in the absence of hyperfine structure is 42 184 180(139) kHz. A new value of the ^{3}He nuclear charge radius is obtained, $\langle r^2\rangle^{1/2}=1.923(36)$ fm, in a regime of low energy and momentum transfer.

PACS number(s): 35.10.Fk, 31.30.Gs, 06.30.Ft

Recent dramatic advances in the theory of helium allow one to extract the different contributions to atomic energies to the full extent of the experimental accuracy [1]. Concerning the isotope shift, the partial cancellation of the less accurate contributing terms allowed Drake [2,3] to give predictions with an uncertainty of 1 kHz, not counting that originating from the finite nuclear size. This contribution can be evaluated in a first-order perturbative scheme, and a laser spectroscopy experiment, if sufficiently accurate, can reach to effects of nuclear structure, and in particular give values for the nuclear radii. Similar effects have for instance become observable on the isotope spectrum of atomic hydrogen [4]. Measurements on helium would offer the further possibility of a comparison not only with results extrapolated from high-energy scattering measurements but eventually also with results from muonic atoms, which for ^{4}He are already available [5,6]. To date, a number of isotope shift investigations were reported for helium [7–11], but only the recent one [12] on the $2\,^3S-2\,^3P$ transition at 1.08 μm provided the high accuracy necessary to test the sum contribution of relativistic recoil, singlet-triplet mixing, volume shift, and quantum electrodynamics. The recent improvement of more than one order of magnitude in the accuracy of the theory [2] allows us now to separate the different physical quantities and directly evidence the contribution of volume shift (VS). In this paper, we report a high-precision measurement of isotope shift of the transition $2\,^3S-3\,^3P$ between ^{3}He and ^{4}He and quantitatively evidence the VS contribution. The reason for choosing this transition, starting from the same level as in [12] but reaching the immediately higher P level, is twofold: slightly better theoretical predictions are possible, because the contribution of less accurate terms is lower for the $3\,^3P$ than for the $2\,^3P$ level; the excitation wavelength at 389 nm can be conveniently produced by doubling the frequency of the radiation from a Ti:sapphire laser, as shown in [13]. This is a crucial feature for the present experiment because it allows the heterodyne measurements of the isotope separation to be performed in the "red," where frequency-stabilized semiconductor diode lasers (SDL's), line narrowed to about 100 kHz by the feedback from a grating [14], can be conveniently used. Indeed, as shown in Fig. 1, a reference, at almost halfway between the resonance half-frequencies of the two isotopes, is created by means of a SDL laser locked to a transmission peak of a thermally stabilized confocal Fabry-Pérot interferometer ($FSR=3$ GHz, finesse 85). The long-term stability of the reference is ensured by locking the interferometer to a second diode laser stabilized on the saturated absorption of a hyperfine component of the D_2 line of ^{87}Rb. Only one frequency doubled Ti:sapphire laser (linewidth 1 MHz) is locked on the sub-Doppler saturation absorption from the $2\,^3S_1$ metastable state prepared in a low-pressure radio-frequency discharge cell alternatively filled with ^{3}He and ^{4}He. Two probe beams, at 389 nm, about 300 μW each, pass through the cell (absorption nearly 30%) and are detected by two different photodiodes. One of the two beams overlaps with counterpropagating pump beam (10 MW). By detecting the difference in the intensities of the two transmitted probe beams, the Gaussian absorption profile is eliminated, the laser amplitude noise is reduced to about 10^{-5} Hz$^{-1/2}$, and sub-Doppler lines are recorded with signal-to-noise ratios of about 1000 in a band-

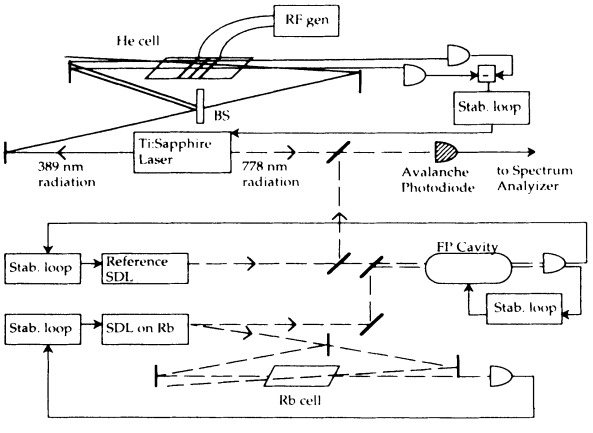

FIG. 1. Scheme of the experimental setup for the isotope-shift measurement on helium. BS denotes a beam splitter, FP denotes a Fabry-Pérot cavity, and SDL denotes a semiconductor diode laser.

*Also at Scuola Normale Superiore, Pisa, Italy.

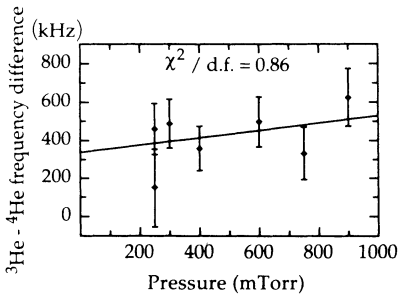

FIG. 2. Isotope frequency separation as measured at different helium discharge pressures (the value of the χ^2 per degree of freedom of the fit is reported inside the box).

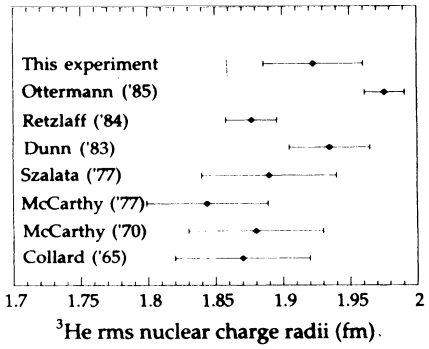

FIG. 3. ^{3}He nuclear radius value obtained in the present work in comparison with those from previous electron-scattering experiments.

width of about 250 Hz. Linewidths, determined by collisional broadening and residual Doppler broadening, are of about 40 MHz, while saturation broadening has been checked to be negligible. The Ti:sapphire laser is frequency modulated at 1.65 KHz, with a modulation depth of about 8 MHz in the "red" and derivative signals are used to frequency lock at the line center. The frequency lock of the two SDL's is obtained by piezoelectrically controlling the grating position as described in [15]. The beat note between the radiations from the undoubled Ti:sapphire laser at 778 nm and the reference SDL, at about 12 GHz, is detected by an avalanche photodiode. In-phase modulation of the two lasers reduces the beat note width. By summing 300 frequency scans of the spectrum analyzer, a width of 2 MHz at -6 dB from maximum is obtained. For each measurement, after relocking the Ti:sapphire laser, we took three independent recordings of the averaged beat note which were stored in a personal computer and fitted to find the central frequency. The value of the frequency separation between the two isotopes was deduced by locking the Ti:sapphire laser consecutively on the $2\,^3S_1-3\,^3P_0$ ^{4}He transition and on the corresponding one for ^{3}He($F=\frac{1}{2}$-$F=\frac{1}{2}$ hyperfine component), while the two semiconductor lasers were kept locked. The isotope separation was obtained by summing the values of the two consecutive measurements and then multiplying by a factor of 2 to deduce the separation at the atomic wavelength. A total of 84 independent measurements were performed at seven different pressures. At the same pressure conditions, the reproducibility was better than 250 kHz. Figure 2 shows the effect of changing the gas pressure in a 250–900 mTorr range. The standard deviation of each sample was divided by the square root of the number of measurements in each run, and the values were fitted to a straight line. The differential pressure shift, between ^{3}He and ^{4}He, is negligible: 0.19 ± 0.22 kHz/mTorr. The zero-pressure value can be extrapolated with an accuracy of 124 kHz (one standard deviation). The final value can be given only after a careful analysis of possible systematic shifts. The beat frequency between the Ti:sapphire laser locked on one isotope and the reference SDL laser has been measured several times by changing the sample discharge current from 50 to 100 mA, and the observed effect was not relevant: 18 ± 23 kHz. In addition, the effect is almost completely cancelled in the difference between the isotopes. Systematic effects can be caused by a slight line asymmetry caused by the presence of a residual magnetic field in combination with a not perfect linear polarization of the laser. We also investigated the Zeeman effect for both the isotopes by applying an external magnetic field. From the collapse of the Zeeman structure we determined the value of the residual magnetic field, yielding a correction of 87 ± 58 kHz for the difference between $^3S_1-^3P_0$ ^{3}He($F=\frac{1}{2}$-$F=\frac{1}{2}$) and of $^3S_1-^3P_0$ ^{4}He transitions. The final corrected value for the isotope separation, reported in Table I, is $45\,394\,425\pm137$ (1σ) kHz, corresponding to an accuracy of 3 ppm. The isotope shift is by definition given by the ^{3}He-^{4}He difference in the absence of the hyperfine interaction in ^{3}He. As a consequence, the comparison between experiment and theory requires the precise evaluation of the fine-hyperfine interaction contributions. These calculations have been performed by Drake [3] to a precision of 20 kHz, following the model used in [16] for the 2^3P level, and the iso-

TABLE I. Isotope-shift theoretical predictions, evidencing the effect of changing the ^{3}He nuclear radius of 0.1 fm, and the experimental value measured in the present work.

Quantity	Value (kHz)	Error (kHz)
Theoretical isotope shift (R_{nuc} ^{3}He=1.875 fm)	42 183 995 (Ref. [3])	1
Theoretical isotope shift (R_{nuc} ^{3}He=1.975 fm)	42 184 383 (Ref. [3])	1
Measured isotope frequency separation	45 394 338	124(1σ)
Hyperfine-structure correction	$-3\,210\,245$ (Ref. [3])	20
Residual-magnetic-field correction	+87	58
Experimental isotope shift	42 184 180	139(1σ)

tope shift value that we deduce from our measurement is reported in Table I. The theoretical predictions are given assuming two different values for ^{3}He nuclear charge radius, while for ^{4}He is used the value of 1.673(1) fm from the muonic atom spectroscopy [5,6], which is in agreement with the less precise value of 1.674(12) fm obtained from electron scattering experiment [23]. The comparison between experiment and theory and a first-order treatment of the nuclear size corrections allows us to give a value of 1.923(36) fm for the ^{3}He nuclear charge radius. This result is shown in Fig. 3 together with previous values from high-energy scattering experiments [17–23]. It is worth noting that our experiment, implying a low momentum transfer, does not suffer from the problems related to the extrapolation of the nuclear charge radius from the form factor which, instead, is necessary in the scattering experiments, where the momentum transfer is five orders of magnitude larger. The improved state of the theoretical predictions allows us now to apply the same comparison procedure to the previous isotope shift measurement on the lower $2\,^3S-2\,^3P$ transition [12]. Indeed, a value of 1.925(8) fm was calculated in [2], where, however, singlet-triplet mixing correction had not been considered for the $2\,^3S_1$ level. By taking into account this correction, reported in [24], we are able to extract from the measurements of Ref. [12] a ^{3}He nuclear radius value of 1.938(10) fm. The agreement with the result from our experiment constitutes evidence of the self-consistency of the measurements from atomic spectroscopy. This supports their possible use in a wider physical context. In the measurements at 1.08 μm, Pipkin and co-workers could benefit from a near coincidence between a ^{3}He hyperfine structure transition and a ^{4}He fine-structure transition, thus reducing the measured difference frequency to values accessible to precise sideband spectroscopy. Our experimental method, also using one single laser at the atomic wavelength, is somewhat more general. It can be extended to a complete investigation of the hyperfine structure, yielding a more complete test of the theory. Also, an improvement of one order of magnitude in the accuracy is foreseen from an atomic beam experiment under development where both systematic and statistical errors are reduced.

A further advantage of the scheme that we have developed for the measurements at 389 nm is the possibility of performing absolute frequency measurements of the atomic transitions [25]. Absolute frequency measurements and a refinement of the atomic theory would make it possible to measure independently the nuclear radius of both the helium isotopes. In the case of ^{4}He, that would allow a fruitful comparison with the radius extracted from Zavattini's experiment [5,6] in which a different lepton probed the nucleus, i.e., a muon instead of an electron.

In conclusion the isotope shift between ^{3}He and ^{4}He of the $2\,^3S-3\,^3P$ transition has been measured with an accuracy of 3 ppm. The analysis of the results has required a comparison with a very refined theoretical model. The contributions of small but qualitatively important effects can be verified. This leads to a new determination of the ^{3}He nuclear charge radius. This result, obtained at low energy and momentum transfer, opens the possibility of a meaningful comparison with values extrapolated from high-energy scattering experiments.

We would like to thank G.W.F. Drake for communicating his results before publication and for many helpful comments. We also thank E. Zavattini for stimulating discussions.

[1] G. W. F. Drake, in *Atomic Physics 13,* edited by T. W. Hänsch, H. Walther, and B. Neizert, AIP Conf. Proc. No. 275 (AIP, New York, 1992), p. 3, and references therein.

[2] G. W. F. Drake, in *Long-Range Casimir Forces: Theory and Recent Experiments on Atomic* Systems, edited by F. S. Levin and D. A. Micha (Plenum, New York, 1993), p. 107.

[3] G. W. F. Drake (private communication).

[4] F. Schmidth-Kaler, D. Leibfried, M. Weitz, and T. W. Hänsch, Phys. Rev. Lett. **70**, 2261 (1993).

[5] G. Carboni, G. Gorini, L. Palffy, F. Palmonari, G. Torelli, and E. Zavattini, Nucl. Phys. **A278**, 381 (1977).

[6] E. Borie and G. A. Rinker, Phys. Rev. A **18**, 324 (1978).

[7] R. R. Freeman, P. F. Liao, R. Panock, and L. M. Humphrey, Phys. Rev. A **22**, 1510 (1980).

[8] E. de Clercq, F. Biraben, E. Giacobino, G. Grynberg, and J. Bauche, J. Phys. B **14**, L183 (1981).

[9] L. A. Bloomfield, H. Gerhardt, and T. W. Hänsch, Phys. Rev. A **27**, 2261 (1983), and references therein.

[10] D. Bloch, G. Trenek, and M. Leduc, J. Phys. B **18**, 1093 (1985), and references therein.

[11] T. van der Veldt, W. Vassen, and W. Hogervost, Phys. Rev. A **41**, 4099 (1990).

[12] P. Zhao, J. R. Lawall, and F. M. Pipkin, Phys. Rev. Lett. **66**, 592 (1991).

[13] C. S. Adams, E. Riis, A. I. Ferguson, and W. R. C. Rowley, Phys. Rev. A **45**, R2667 (1992).

[14] G. M. Tino, L. Hollberg, A. Sasso, M. Barsanti, and M. Inguscio, Phys. Rev. Lett. **64**, 2999 (1990).

[15] F. Marin, P. DeNatale, M. Inguscio, M. Prevedelli, L. R. Zink, and G. M. Tino, Opt. Lett. **17**, 148 (1992).

[16] E. A. Hinds, D. J. Prestage, and F. M. J. Pichanick, Phys. Rev. A **32**, 2615 (1985).

[17] H. Collard, R. Hofstadter, E. B. Hughes, A. Johansson, and M. R. Yearian, Phys. Rev. **138**, B57 (1965).

[18] J. S. McCarthy, I. Sick, R. R. Whitney, and M. R. Yearian, Phys. Rev. Lett. **25**, 884 (1970).

[19] J. S. McCarthy, I. Sick, and R. R. Whitney, Phys. Rev. C **15**, 1396 (1977).

[20] Z. M. Szalata, J. M. Finn, J. Flanz, F. J. Kline, G. A. Peterson, J. W. Lightbody, Jr., X. K. Maruyama, and S. Penner, Phys. Rev. C **15**, 1200 (1977).

[21] P. C. Dunn, S. B. Kowalski, F. N. Rad, C. P. Sargent, W. E. Turchinetz, R. Goloskie, and D. P. Saylor, Phys. Rev. C **27**, 71 (1983).

[22] G. A. Retzlaff and D. M. Skopik, Phys. Rev. C **29**, 1194

(1984).

[23] I. Sick, J. S. McCarthy, and R. R. Whitney, Phys. Lett. **64B**, 33 (1976).

[24] E. Riis, A. G. Sinclair, O. Poulsen, G. W. F. Drake, W. R. C. Rowley, and A. P. Levick, Phys. Rev. A **49**, 207 (1994).

[25] F. Marin, F. Minardi, F. Pavone, and M. Inguscio, in *Laser Spectroscopy XI,* edited by A. Bloomfield, T. F. Gallagher, and T. J. Larson (AIP New York, in press).