Three-Nucleon Charge Radius: A Precise Laser Determination Using ^{3}He

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The isotope shift of the 2^3S_1-2^3P_0 transition in helium has been measured using laser excitation of an atomic beam, yielding 33 668.074(5) MHz. This value, combined with atomic theory and the ^{4}He nuclear charge radius, gives a ^{3}He radius of 1.9506(14) fm. This result is over an order of magnitude more precise than previous determinations. It agrees with two recent theoretical values 1.958(6) and 1.954(7) fm from realistic nucleon-nucleon potentials and the ^{3}He binding energy. Our result provides both a confirmation and a sensitive test of the nuclear theory of few-nucleon systems.

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The ^{3}He nucleus is important for understanding nuclear forces and for testing few-nucleon theory [1]. Additionally, the ^{3}He nucleus is of interest in particle physics, where spin polarized ^{3}He serves as a neutron target for spin structure experiments [2], with small corrections arising from nuclear structure [3]. In atomic physics the ^{3}He nucleus has begun to limit the precision with which atomic theory and experiment can be compared [4–6]. This last situation provides an opportunity to determine precisely a basic nuclear property of ^{3}He, its root mean square (rms) charge radius, with a precision much greater than was previously possible. We report a precise value for the ^{3}He nuclear radius, 1.9506(14) fm. This result provides a confirmation of the predicted radius from nuclear few-body theory and a sensitive test of future improvements in theory. This nuclear theory may in turn have significant consequences for precise atomic tests of QED. One such consequence is a better understanding of nuclear polarization effects; another, discussed at the end of this paper, is a method to improve the determination of the proton charge radius.

Many properties of three-nucleon [7] systems can be accurately calculated from nucleon-nucleon force models, such as the Nijmegen [8], Paris [9], Argonne AV14 [10], and Bonn [11] potentials. In particular, many bound state properties, including the charge radii, are calculated with near negligible error in comparison with the differences produced by the various nuclear force models themselves. Thus, precise charge radii can test the computational techniques and approaches, as well as the underlying force models. These models of the nucleon-nucleon interaction successfully describe long and intermediate range nuclear forces through single and multiple pion exchange. Various methods for treating shorter range interactions are more phenomenological, and parameters in the models are typically adjusted to best fit two-nucleon experimental data. The connection between these approaches to nuclear forces and the underlying strong interactions described by QCD has been made much clearer recently. Weinberg [12] and Ordonez and van Kolck [13] have shown the form and expected order of various terms in the *NN* potential by using effective Lagrangians and chiral symmetry. While these chiral Lagrangians currently fit two-nucleon data with less precision than well developed traditional approaches [14], their systematic expansion and close connection with QCD should make them increasingly important in the future. Precise nuclear charge radii could provide useful additional information on a number of relevant issues, such as the role of three-nucleon forces, the proper incorporation of relativistic effects, and the importance of nonlocal vs local potentials. For example, different models make different size predictions for ^{3}He even when corrected to the ^{3}He binding energy. A precise measurement is required though, since recent calculations [15,16] using various realistic *NN* models and fitted to the ^{3}He binding energy find a range of radii much smaller than previous experimental uncertainties.

A global fit to all previous electron scattering data on the ^{3}He nuclear charge radius [17] gives an uncertainty of 0.03 fm (0.80 fm for the corresponding analysis in ^{3}H), see Table I and Fig. 1. Electron scattering is a powerful probe of the structure of nuclei in general and ^{3}He in particular but normalization problems limit the precision with which rms radii can be obtained [17]. On the other hand, experiments with bound electrons or muons are ideally suited for such determinations [18], and thus compliment the electromagnetic form factor measurements from electron scattering.

Our experimental approach is to precisely measure a ^{3}He/^{4}He isotope shift in an electronic transition. In

TABLE I. Recent results for the ^{3}He nuclear charge radius.

Experiment	r_c (fm)	Ref.	Theory	r_c (fm)	Ref.
Amroun (94)	1.959(30)	[17]	Wu (93)	1.958(6)	[15]
Marin (94)	1.923(36)	[6]	Friar (93)	1.954(7)[a]	[16]
This work	1.9506(14)				

[a]This 0.007 fm uncertainty is the quadrature sum of 0.005 fm from the variations in various nuclear force model predictions and 0.005 fm from the uncertainty in the proton radius 0.862(12) fm [32]. Meson exchange and relativistic effects may also be expected to contribute at this level but are not yet included.

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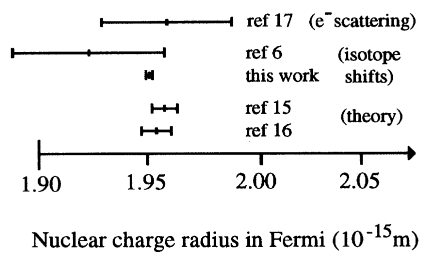

FIG. 1. Recent results for the ^{3}He nuclear charge radius.

isotope shifts of light nuclei, the nuclear volume shift is very small compared to the mass shift, and it has not been possible to extract nuclear charge radii (or differences) with the needed accuracy. With recent advances in theory and experiment, this situation has changed for both one [19,20] and two [4–6,21] electron systems. Thus, due to the nuclear volume shift, a comparison of theory and experiment in helium leads to a value of the difference in the nuclear charge radii of ^{3}He and ^{4}He. Using the precisely known ^{4}He nuclear charge radius 1.673(1) fm [22], we then obtain the ^{3}He nuclear charge radius.

Our experiment studies the isotope shift of the 2^3S-2^3P transition at 1.083 μm (Fig. 2). It has a reasonably large volume shift and can be conveniently excited with a solid state infrared laser (LNA laser). To detect the transition, we use a modification of the well known Rabi molecular beam magnetic resonance technique in which the magnetic resonance is replaced by a depolarizing laser resonance. We recently reported a measurement of the 2^3S_1-$2^3P_{J=0,1,2}$ transition energy and fine structure in ^{4}He using the same techniques and apparatus [23]. The "flop out" geometry generated an on resonance to off resonance count ratio of ~100. Each of the allowed transitions was observed with a 2 MHz linewidth due to the 1.6 MHz natural linewidth, laser power broadening, and Doppler broadening from residual atomic beam divergence. The line centers are determined to 0.1% of the 2 MHz linewidth with 3–4 min of counting.

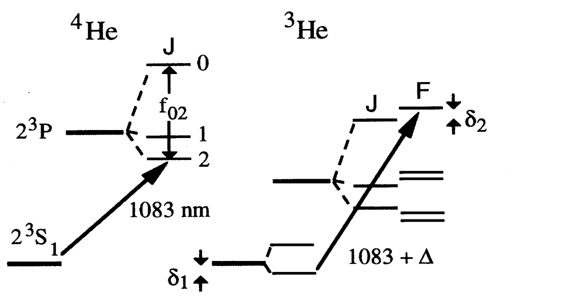

FIG. 2. The relevant levels and intervals for the ^{4}He/^{3}He isotope shift.

We determine the isotope shift of the 2^3S_1-2^3P_0 transition in three steps (see Fig. 2). First, corrections for the hyperfine structure of ^{3}He are needed. The hyperfine structure shifts the $2^3S_1(F = \frac{3}{2})$ level a precisely known amount, 2246.5873 MHz [24], (δ_1). It also shifts the fairly well isolated $2^3P_0(F = \frac{1}{2})$ level by a comparatively small 323.9503(12) MHz according to our $2^3P_{J=1,2}(F = \frac{1}{2}, \frac{3}{2}, \frac{5}{2})$ hyperfine measurements. For the present precision, this value is adequately confirmed by a first order theoretical calculation 323.9541 MHz [25]. Details of our hyperfine measurements and fits will be described elsewhere [26]. Here we use our experimental value, 323.9503(12) MHz, (δ_2).

Second, we measure the small difference Δ in frequency between the ^{3}He $2^3S_1(F = \frac{3}{2}) \rightarrow 2^3P_0(F = \frac{1}{2})$ transition and the ^{4}He $2^3S_1 \rightarrow 2^3P_2$ transition. We obtain $\Delta = 810.599(3)$ MHz, consistent with a previous measurement of 810.608(30) MHz [4], but an order of magnitude more precise. The dominant source of random error in this measurement comes from magnetic field drifts, which were calibrated before and after using $2^3S_1 \rightarrow 2^3P_2(m = \pm 1)$ transitions in ^{4}He. Systematic checks were performed to verify this and other results, such as the important value of f_{02} given below. The magnetic field was changed between 5 and 40 G, with results tracking the well understood Zeeman corrections. The line shape is expected to be symmetric (no significant overlapping transitions, nearby resonances, laser power variations, etc.). This was verified by taking data at two laser frequencies centered on the line and separated by either 1, 2, 4, or 8 MHz with no change in line center observed. Measurements at various laser powers show a linear power shift that at the normal laser power shifts the intervals by ~1 kHz. The size of Doppler shifts are minimized by retroreflection and verified by, among other things, cooling the beam to 77 K. Tables II and III show uncertainty estimates and results after averaging several measurements. An important independent check on our error estimates for the various transitions we measure comes from our agreement (~3 kHz) with the accurately known ^{3}He 2^3S hyperfine structure splitting [24].

Third, the $J = 2$ to $J = 0$ fine structure interval of ^{4}He, $f_{02} = 31\,908.135(3)$, obtained from our recently reported

TABLE II. Uncertainty budget (kHz, 1 standard deviation).

Source	Δ	hfs	f_{02}
Random	1.3	2.2	0.8
Wavelength metrology	2.0	2.0	2.0
First order Doppler	1.5	2.0	1.0
Laser power/line shape	1.5	2.0	1.0
Other (second order Doppler, B field, recoil, rf standards)	<1.0	<1.0	<1.0
Total (rms sum)	3	4	3

TABLE III. Results for (1) the frequency difference of the ^{3}He $2^3S_1(F = \frac{3}{2}) \rightarrow 2^3P_0$ and ^{4}He $2^3S_1 \rightarrow 2^3P_2$ transitions, labeled Δ; (2) the ^{3}He 2^3S_1 hyperfine splitting; (3) the ^{4}He $2^3P_0 \rightarrow 2^3P_2$ interval, labeled f_{02}; (4) the ^{3}He/^{4}He $2^3S_1 \rightarrow 2^3P_0$ isotope shift; and (4) the rms nuclear charge radii R_{nuc}. The first two rows show errors in the mean after six trials, the fourth row includes systematic errors (MHz, 1 standard deviation).

Source	Δ	^{3}He 2^3S_1 hfs	f_{02}
Dielectric mirrors	810.5994(15)[a]	6739.6997(28)[a]	31 908.1339(9)
Silvered mirrors	810.5980(24)	6739.6969(36)	31 908.1369(17)
Combined results (random errors)	810.5987(13)	6739.6983(22)	31 908.1354(8)
Final results (total errors)	810.599(3)	6739.698(4)	31 908.135(3)
Previous results	810.608(30)[b]	6739.701 177(16)[c]	31 908.040(20)[d]
Difference	−0.009(30)	−0.003(4)	0.095(20)

Isotope shift $\delta_1 + \delta_2 - \Delta + f_{02} = 33\,668.074(5)$ MHz $\Rightarrow$
$R_{\text{nuc}}(^3\text{He}) - R_{\text{nuc}}(^4\text{He}) = 0.2776(10)$ fm
$R_{\text{nuc}}(^3\text{He}) = 1.673(1)^{\text{e}} + 0.2776(10) = 1.9506(14)$ fm

[a]13 trials.
[b]Ref. [4].
[c]Ref. [24].
[d]Ref. [28].
[e]Ref. [22].

measurements is required [23,27]. The dominant uncertainty comes from wavelength metrology, where we determine the 32 GHz interval using the virtual mirror technique with 1 and 3 m etalons (once known, this larger interval serves to calibrate the interferometer's free spectral range, used in making the smaller frequency interval measurements). Random errors in the virtual mirror technique come from mirror imperfections (nonuniformity in phase shift and curvature). They are studied and minimized by measuring mirror curvatures *in situ,* changing the laser spot location on the mirror, and simply repeating the whole virtual mirror technique several times. An important check on possible systematic errors is done by not only switching between nominally identical mirrors, but by using two completely different mirror types: dielectric, having high reflectivity and finesse but large phase shifts, and silvered, having small phase shifts but low reflectivity and finesse. The results of Table III lead us to assign a ± 2 kHz uncertainty from wavelength metrology. We caution the reader that our f_{02} value is not in good agreement with a previous experiment [28], which gives $f_{02} = 31\,908.040(20)$ MHz. Since this frequency interval is a promising source of a precise value for the fine structure constant α, both experimental and theoretical [29,30] work continues on this interval, and this effort will further serve as a check on our result. Using our value for f_{02}, the experimental isotope shift of the 2^3S_1-2^3P_0 transition can then be determined: I.S. $= \delta_1 + \delta_2 - \Delta + f_{02} = 33\,668.074(5)$ MHz.

The theoretical isotope shift for this transition has only a 1 kHz error if the difference in the ^{3}He/^{4}He nuclear charge radius is known [5]. Alternatively, atomic theory and experiment can be combined to deduce a ^{3}He/^{4}He nuclear charge radius difference of 0.2776(10) fm (using the analysis and results of Refs. [5] and [31]), and a ^{3}He nuclear charge radius of 1.9506(14) fm. We estimate nuclear polarization effects [22,29] will contribute $\sim 1-2$ kHz, and they are not included.

The precision of the ^{3}He nuclear charge radius reported here, 1.9506(14) fm, is significantly improved over previous determinations and provides a confirmation of theoretical predictions 1.958(6) fm [15] and 1.954(7) fm [16]. How this comparison will change once relativistic and meson exchange corrections are incorporated is an interesting problem for theory. Of course further improvements in the nuclear force models can be expected as a better understanding of the nuclear force is developed. With regard to the atomic physics of ^{3}He, it is clear that the necessary high precision is both achievable and worthy of effort. To insure the accuracy of our result, just as with any other precision measurement, it is essential to perform confirming experiments of equivalent (or possibly much better) precision having substantially different systematic errors. This is certainly feasible, and given our disagreement with the previous value of f_{02}, particularly important. Nevertheless, the agreement between current theory and experiment is striking, and we look forward to interesting comparisons in the future.

We close by noting that the theoretical prediction for the difference in radii between tritium and ^{3}He should have an uncertainty much smaller than the absolute radius, which has a precision of ~ 0.007 fm. Precise isotope shift measurements could then tie all $A \leq 4$ nuclear radii together. For example, tritium/hydrogen and ^{3}He/^{4}He isotope shifts could in principle improve knowledge of the proton radius, which is 0.862(12) fm [32], to a precision equal to the uncertainty of the ^{4}He radius, currently 0.001 fm. At present the deuterium/hydrogen isotope shift measurements are at the 0.006 fm level [19,20], and can be expected to soon reach the 0.001 fm level reported here.

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