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Towards Measuring the Charge Radius of ^{6}He and ^{8}He

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Abstract

We report on the progress towards measuring the charge radius of ^{6}He and ^{8}He nuclei by performing laser spectroscopy on these helium atoms in a magneto optical trap (MOT). First tests to produce neutral ^{6}He atoms via the ^{12}C(^{7}Li,^{6}He)^{13}N reaction at the ATLAS accelerator have been successfully conducted. The MOT apparatus including the laser system and the discharge source to populate the metastable level are currently being set up.

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1. Introduction

The short-lived isotopes ^{6}He ($t_{1/2}$ = 807 ms) and ^{8}He ($t_{1/2}$ = 119 ms) exhibit a loosely bound neutron halo around a ^{4}He-like core. Such a nuclear structure offers the unique

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opportunity to study interactions in low-density neutron-rich nuclear matter. The interaction radii of these nuclei have been measured by elastic scattering on protons [1]. Calculation of the matter- and charge-radii based on these results are however highly model dependent. No direct measurements of the respective charge radii have been reported so far. Any difference in charge radii of ^{6}He and ^{8}He compared to ^{4}He can be attributed to the interaction of the neutron halo with the ^{4}He-like core. Thus a precision measurement of the charge radii will probe the wavefunction of the halo-neutrons and help study the isospin dependence of the three-nucleon force. Recent advancements in Quantum Monte Carlo calculations of few-body nuclei [2] has enabled a precise prediction of the charge radii of ^{6}He and ^{8}He. A respective measurement would test this theory in the high-isospin region away from nuclear stability.

Our approach in determining the charge radii is based on the measurement of the isotope shift of atomic transitions. The isotope shift has two contributions: the mass shift and the field shift. The mass shift is determined by the change in nuclear mass, the field shift depends on the difference in rms charge radii. To extract the latter from an isotope shift measurement a precise knowledge of the atomic structure and of the nuclear masses is required. The isotope shift of the $2\ ^3S_1$ - $2\ ^3P_0$ transition between ^{4}He and ^{3}He was measured to be 33,668.074(5) MHz [3], of which about 1 MHz is from the field shift. Based on a precise atomic theory of helium [4], the nuclear masses of ^{3}He and ^{4}He [5], and the charge radius of ^{4}He determined by spectroscopy of muonic ^{4}He atoms, the charge radius of ^{3}He was deduced to be 1.9506(14) fm. Similar isotope shift measurements for ^{6}He and ^{8}He can be used to determine the charge radii of these isotopes. If the isotope shift is measured to a precision of 100 kHz, the charge radius can be extracted with an error of about 5%. The uncertainty in atomic theory for the 2 $^3S_1$ - 2 $^3P_0$ isotope shift is about 11 kHz for ^{6}He and 85 kHz for ^{8}He, and is predominantly due to uncertainties in the nuclear masses. Direct mass measurements of both isotopes could further reduce these uncertainties [6].

While the nuclear properties of many stable and unstable isotopes have been measured using various laser spectroscopy techniques, measurements of the charge radii of ^{6}He and ^{8}He have so far been too difficult for a number of reasons. First of all, the production rates for both isotopes at existing on-line facilities are low, and the lifetimes of the isotopes are short. Secondly, the first excited level of helium is at 20 eV above the ground-level, making it impossible to perform precision laser spectroscopy out of the ground-level due to a lack of narrow-band VUV lasers. High-resolution measurements have to use transitions from metastable levels, which have convenient wavelength attainable by narrow-band cw-lasers, but suffer from the low efficiency of populating the metastable level. Furthermore, the requirement of measuring isotope shifts to sub-MHz precision is in general not satisfied by previous on-line laser spectroscopic methods that could cope with low production rates.

We have recently developed a method that combines high resolution with high sensitivity [7]. This method, called Atom Trap Trace Analysis, is based on trapping the desired isotope selectively and efficiently in a magneto-optical trap (MOT) and detecting it by observation of the fluorescence light. The capabilities of ATTA have been demonstrated on the ultra-trace detection of the long-lived isotopes ^{85}Kr and ^{81}Kr. ATTA has shown to be able to detect single atoms by providing long observation time of a spatially confined atom. Additionally, the atom is inherently cooled while in the trap and the Doppler broadening is well below the natural linewidth, permitting the required spectroscopic resolution. ATTA should allow us to perform the spectroscopic measurement by observing the fluorescence signal of a single atom in dependence of the laser detuning. Hence, data will only be taken when a ^{6}He or ^{8}He atom is actually present in the trap, background will be largely avoided.

Trapping of ^{4}He in a MOT has been demonstrated by various groups [8,9]. Helium can be conveniently trapped using the closed 2 $^{3}S_{1}$ – 2 $^{3}P_{2}$ transition at 1.083 μm. Prior to trapping, the Helium atoms have to be excited to the metastable level in a discharge source. The complete experimental setup will include a target chamber for on-line production of the short-lived isotopes with subsequent neutral extraction and transfer to the discharge source, a Zeeman slower to decelerate the thermal beam of metastable He, a MOT with single atom detection capability and a laser system to produce the light for trapping and high resolution spectroscopy. Here we present the results of a first production test for ^{6}He at the ATLAS accelerator at Argonne and the progress in setting up the MOT apparatus.

2. ^{6}He production test

To be able to trap the short-lived ^{6}He and ^{8}He they must be available as thermal neutral atoms. The experimental setup for the on-line production must therefore provide an efficient production, neutralization and fast effusion of the isotopes. Subsequently, the atoms have to be compressed and transferred to the discharge source. A sketch of our setup for the on-line production of ^{6}He at the ATLAS accelerator is shown in Fig. 1. ^{6}He is produced via the $^{12}C(^{7}Li,^{6}He)^{13}N$ reaction and stopped in a thick porous graphite target.

The target is radiatively heated to 750° C by a tungsten filament. The neutral atoms diffusing out of the target are compressed by a turbo pump system into a small vacuum chamber. A plastic scintillation detector adjacent to the chamber served to detect the β radiation from the ^{6}He decay with an efficiency of about 5%. We verified that the observed β particles were indeed emitted by ^{6}He based on the measured energy spectrum as seen in Fig. 2a and the half-life of the β emission after shutting of the detection chamber with two valves as shown in Fig. 2b. Both the observed end point energy of 3.5 MeV and the half-life of about 800 ms agree very well with the known values for ^{6}He. From the total β count rate we can derive that, at a ^{7}Li beam current of 20 pnA, ^{6}He atoms were extracted at a rate of about 3×10^{5} /s. We expect that at ATLAS we can extract ^{6}He at a rate of up to 1×10^{7} /s simply by increasing the ^{7}Li current.

Further ^{6}He production tests at ATLAS will be conducted to verify the production rate at higher ^{7}Li current and to test other production reactions. Due to the shorter half-life of ^{8}He compared to ^{6}He the experiment requires a ten times higher extraction rate to achieve the same signal-to-noise ratio. However, achievable ^{8}He production rates at ATLAS are much lower than for ^{6}He ($\sim10^{2}$/s). Potential on-line facilities to conduct the ^{8}He measurement are ISAC at TRIUMF, ISOLDE at CERN or the proposed Radioactive Isotope Accelerator in the US.

3. MOT apparatus and laser system

The MOT apparatus and the laser system for trapping and spectroscopy is currently being set up. The source for the metastable atoms is an inductively coupled, RF driven discharge [10]. Compared to more conventional DC driven discharge sources operating at pressures of a few Torr, the RF driven discharge works at pressures of only a few mTorr. This results in a fast transit time of the atoms. The source has been proven to work very reliable in the krypton setup and to produce a metastable population of about 10^{-4} to 10^{-3} relative to ground state atoms. First tests indicate that it also operates well with He at pressures of 10 to 20 mTorr, but the relative metastable population seems to be one to two orders of magnitude lower. This could be partly due to the higher energy of the metastable level in He compared to Kr, but an increase of RF power and changes in the source geometry are expected to still increase the metastable population.

The beam of metastable He effusing from the source will be transversally cooled by four perpendicular laser beams to decrease the beam divergence. Subsequently, the atoms are decelerated by the Zeeman-slowing technique inside a 170 cm long, tapered solenoid. The MOT coils are mounted in vacuum to permit fast switching of the magnetic field by avoiding eddy currents and providing low inductivity. Fast switching is required to be able to alternate quickly between performing field-free spectroscopy and retrapping of the atoms.

An external cavity diode laser that is amplified by an Ytterbium fiber amplifier provides the laser light for trapping at 1083 nm. The maximum output power of the amplifier is 1 W, which is more than sufficient to provide light for the transverse cooling, the Zeeman slowing and the trapping. The diode laser is offset stabilized to a helium reference cell with the help of acousto-optical modulators. The isotope shift measurement will be performed in the $2\ ^3S_1 - 3\ ^3P_2$ transition at 389 nm. This avoids background from the trapping light and enables efficient detection of the fluorescence light by using single photon detectors, which are not available at 1083 nm. The blue light will be produced by frequency doubling the 778 nm light from a tapered amplifier. The frequency of the 778 nm laser will be measured by optical beating with a reference laser either stabilized to rubidium or iodine.

4. Outlook

We are currently in the process of assembling the MOT apparatus and the laser system. After thorough tests and optimization of all the components we first have to demonstrate the ability to do the spectroscopy with single atoms with an efficiency that is sufficient for the obtainable production rate of ^{6}He. Additionally, we have to evaluate the achievable spectroscopic precision with measurements on the fine-structure of ^{4}He and the hyperfine-structure of ^{3}He. Afterwards we will move the apparatus to the ATLAS accelerator to do the on-line experiment on ^{6}He. Measurements on ^{8}He will have to wait until the experiment on ^{6}He has proven to be successful and a suitable on-line facility is found.

Acknowledgements

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Figure Captions:

Fig. 1 Sketch of the experimental setup for the production and extraction of neutral ^{6}He atoms

Fig. 2 (a) Energy spectrum and (b) decay curve of the detected β particles during the ^{6}He-production test

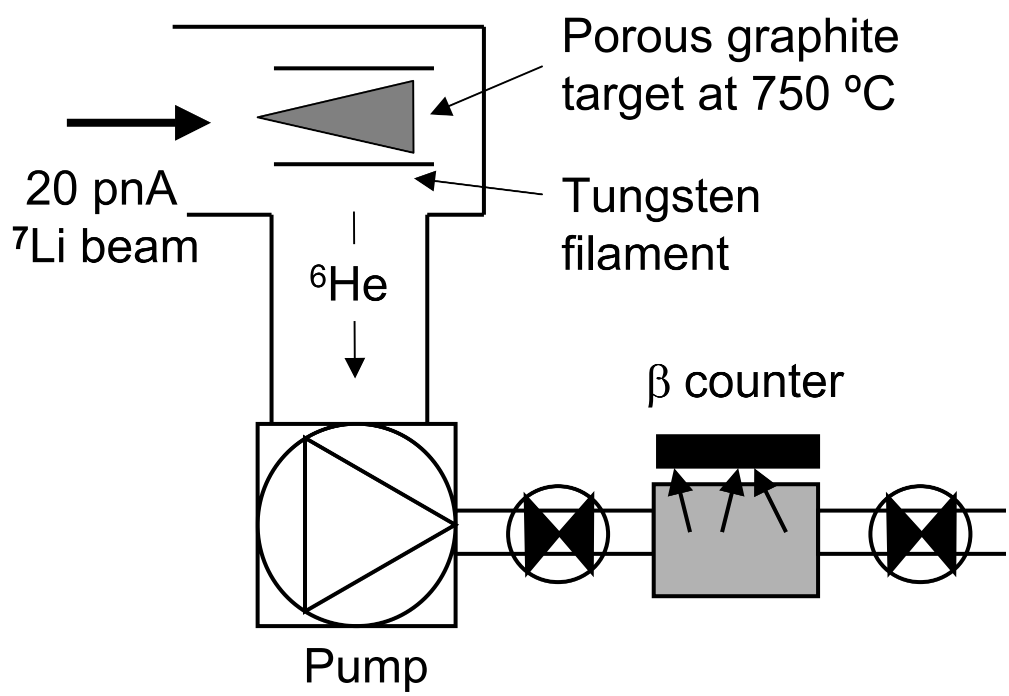
Porous graphite
target at 750 ºC
20 pnA
⁷Li beam
Tungsten
filament
⁶He
β counter
Pump

Fig. 1

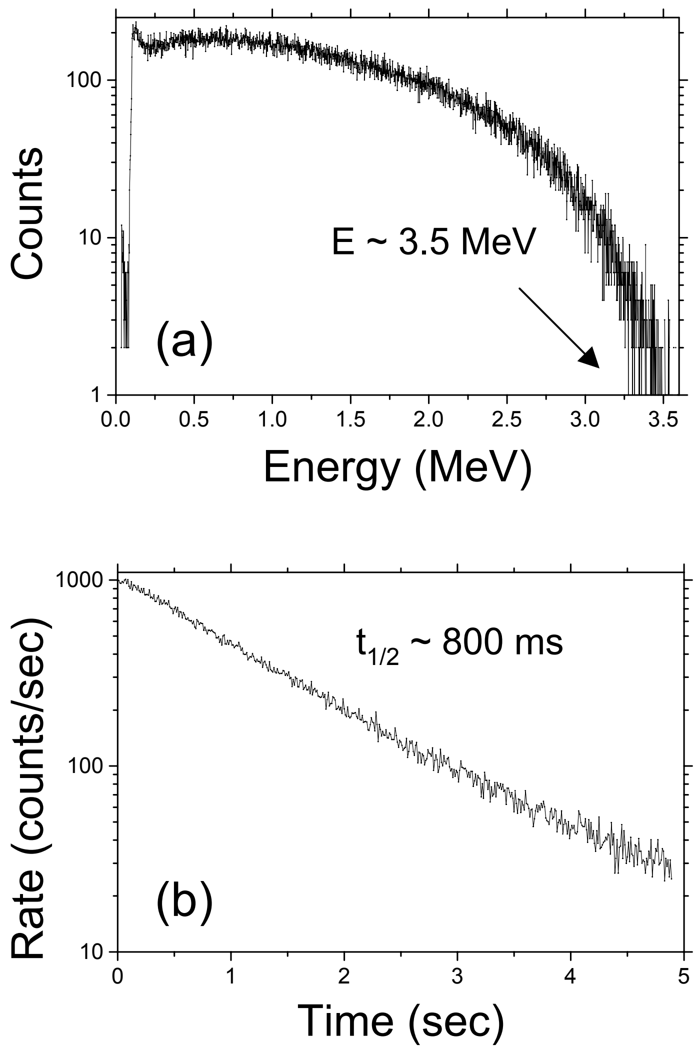
Counts
100
10
1
E ~ 3.5 MeV
(a)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Energy (MeV)
Rate (counts/sec)
1000
100
10
$t_{1/2}$ ~ 800 ms
(b)
0
1
2
3
4
5
Time (sec)

Fig. 2