Proposal for an experiment at REX-ISOLDE

Study of the deuteron emission in the β decay of ^{6}He

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Abstract

The main goal of the present proposal is to measure the continuous spectrum of deuterons emitted in the β-decay of ^{6}He. In particular, we want to focus on the low energy part of the spectrum, below 400 keV, which could not be accessed by all previous experiments. For the decay spectroscopy the Warsaw Optical Time Projection Chamber (OTPC) will be used. The bunches of ^{6}He ions produced by REX-ISOLDE facility will be implanted into the active volume of the OTPC, where the rare events of deuteron emission will be recorded, practically background free.

1. Introduction

The physics of nuclear halo continues to be one of the most active fields of research. The possibility of factorization of the wave function into a core and halo components simplifies considerably the description of the system. This in turn, provides rigorous tests to models of nuclear structure. In this proposal we address the question of the β decay of ^{6}He which can be considered as a simple two-neutron halo system ($\alpha + 2n$). This nucleus has a half-life of 810 ms and has a rather simple decay scheme. Predominantly, it decays by a Gamow-Teller transition to the ground state of the stable ^{6}Li ($Q = 3.508$ MeV). With a very small probability, of the order of 10^{-6}, however, the decay proceeds to the final state of an α particle and a deuteron, in a process called β-delayed deuteron emission. The energy spectrum of the ($\alpha + d$) system is continuous with the maximum energy of 2.0 MeV. Such a decay branch is of great interest because its probability (branching ratio) is very sensitive to the details of the initial ^{6}He wave function, in particular of its external parts, and to the precise description of the $\alpha + d$ scattering states. This case may serve as a perfect example of the β decay as an accurate probe of the halo structure.

The β-delayed deuteron emission from ^{6}He has been a subject of experimental studies for 20 years [1-4]. After an initial controversy concerning the total branching ratio for this transition, the most recent and the most accurate value is $b_{d,E>350} = (1.65 \pm 0.10) \cdot 10^{-6}$ for the deuteron energy $E_d \geq 350$ keV [4]. The corresponding spectrum is shown in Figure 1, together with results from the previous experiment [3] and with the recent theoretical prediction [5].

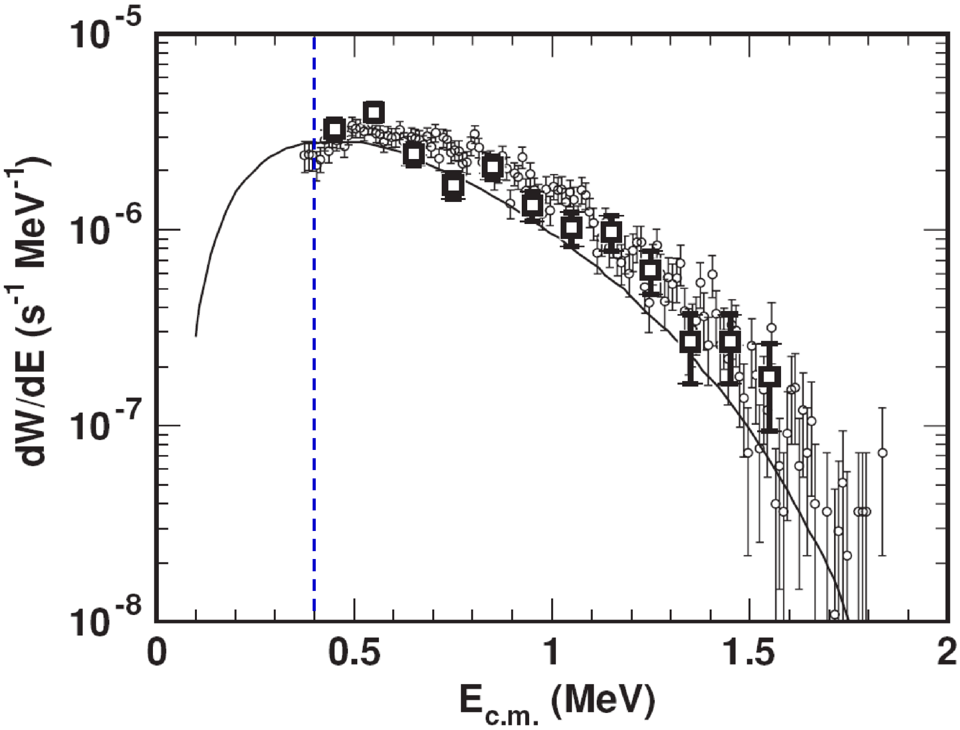

Figure 1. Transition probability for the α + d decay branch of ^{6}He as a function of center-of-mass energy. The squares represent results from Ref. [4] and circles are data from Ref. [3]. The solid line shows the prediction from Ref. [5] (figure taken from Ref. [4]).

In this theoretical study, the ^{6}He was treated in a $\alpha + n + n$ three-body cluster model in hypershperical coordinates, while a potential model was used for the description of the $\alpha + d$ system [5]. The very small value of the branching ratio is found to result from cancellations in the Gamow-Teller matrix element between contributions from different parts of the spatial integral. With the proper selection of the model parameters, however, the model reproduces rather well the intensity and the shape of the measured data, although the maximum of the predicted curve appears to be shifted with respect to the experimental one. This is an important point to settle since the spectral shape and intensity are coupled in the theoretical calculations [5]. From the theoretical analysis, and from data shown in Figure 1, it follows that the better constrains on the model parameters, and thus better understanding of the structure of the initial halo wave function, requires measuring the $\alpha + d$ spectrum down to at least 200 keV (to track the fall off in intensity), below the current experimental threshold of about 400 keV [4]. The reason for this threshold is of purely experimental nature. In all previous experiments the charged particles were recorded by means of silicon detectors which are sensitive also to the electrons emitted in the β decay of ^{6}He. The pile-up and summing effects induced by these electrons do not allow for the precise determination of the d (and α) spectrum at low energy.

The aim of the present proposal is to apply a radically different experimental technique to independently measure the shape of the $\alpha + d$ energy spectrum of ^{6}He and to extend it below the threshold of 400 keV.

2. Optical Time Projection Chamber

The key element of the proposed experiment is a new type of the gaseous ionization detector developed at University of Warsaw. It combines the standard time projection chamber technique with the optical readout of signals – the result is called Optical Time Projection Chamber (OTPC) – which allows recording images of tracks of charged particles, and their reconstruction in three dimensions [6,7]. The principle of operation of this detector is shown in Figure 2. The charged particles traversing the active volume ionize the counting gas. The primary ionization electrons drift in a uniform electric field towards the amplification structure where emission of light occurs. This light is recorded by means of a CCD camera, and a photomultiplier tube (PMT). The camera image, accumulated over selected exposure time, shows projection of particles' tracks on the plane perpendicular to the electric field . The signals from the PMT, sampled by a digital oscilloscope, represent the total light intensity as a function of time. They provide information on the sequence of events in the chamber and on the drift-time which is related to the position along the electric field lines.

Originally, the OTPC detector was developed to study the *2p* radioactivity. It was applied very successfully in an experiment made at the MSU/NSCL laboratory yielding the full picture of proton-proton correlations in the decay of ^{45}Fe [8,9]. In addition, the β decay branches of ^{45}Fe accompanied by protons could be observed, including the β-delayed three-proton emission [10]. The latter channel, observed for the first time illustrates extreme sensitivity of the OTPC detector – essentially a single event suffices to establish unambiguously the occurrence of a decay channel. Recently, an improved version of the OTPC was applied to the β-decay study of ^{8}He [11]. An example of a recorded decay event, corresponding to the transition $^{8}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + {}^{3}\mathrm{H} + n$ is shown in Figure 3.

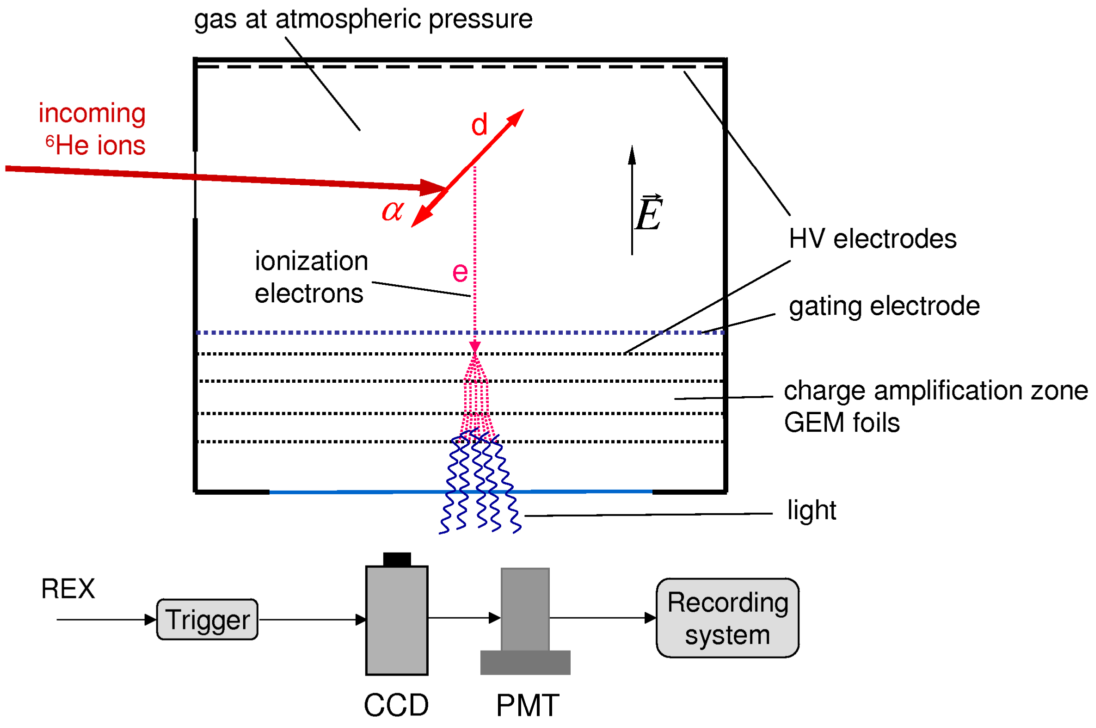

Figure 2. A schematical view of the Optical Time Projection Chamber (OTPC). For each recorded event, the data consist of a 2D image taken by a CCD camera in a given exposure time and the total light intensity detected by a photomultiplier (PMT) as a function of time, sampled by a digital oscilloscope. The gating electrode is used to block the charge induced by incoming ions.

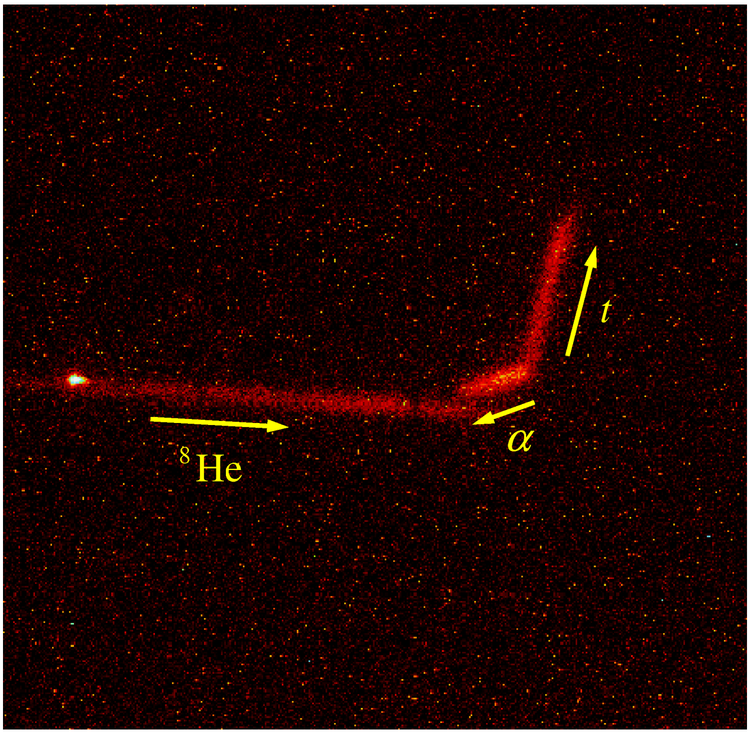

Figure 3. An example CCD image of a β-delayed triton decay of ^{8}He. The OTPC was filled mainly with helium at atmospheric pressure. The exposure time was 1 s. The track of an ^{8}He ion entering the detector from the left is seen. The track of a triton is 35 mm long and corresponds to (640 ± 40) keV. The track of an α particle has 18 mm and corresponds to (1000 ± 50) keV. The neutron and the electron also emitted in this decay are not seen.

If all charged particles emitted in the decay are stopped within the OTPC active volume, their kinetic energies can be determined. This can be done using different methods: by measuring the total light intensity recorded by both the CCD camera and the PMT, by examining the length of the tracks, and by the analysis of the ionization density profile along the tracks. The decay of ^{6}He into $\alpha + d$ will show a characteristic pattern: both particles will be emitted in almost opposite directions, with the less ionizing deuteron taking 2/3 of their total energy. From the analysis of the collected decay events and with help of the simulation program SRIM [12], we conclude that in the case of ^{6}He decay, the OTPC detector should allow the measurement of the $\alpha + d$ energy down to 150 keV with the resolution of 10% or better. We foresee that the counting gas will be pure helium, with a small admixture of nitrogen (about 1%), at the atmospheric pressure. Then, an event corresponding to the energy of 150 keV will consist of a 12 mm long track of the 100 keV deuteron and a 5 mm long track of the 50 keV α particle. On the other hand, for the decay energy of 1 MeV, a track of the deuteron (667 keV) will be 50 mm long, while that of the α particle (333 keV) will have 13 mm. In case of larger energies, some deuterons may escape the OTPC volume.

It is important to note that electrons emitted in the β decay are not detected by the OTPC because of too small ionization they cause. Thus, the measured energy spectrum will not be influenced by summing effects of electrons in contrast to previous experiments.

Another important feature of the OTPC detector is the possibility to drastically reduce its sensitivity, and thus to protect the multiplication stages, by means of a special gating electrode (see Figure 2). We plan to use this possibility to operate the detector in the following mode. First, when the OTPC is in the blocked state (low sensitivity) a bunch of ^{6}He ions (10^{4} or more) will be implanted. After several milliseconds, when all ionization charges induced by these ions are removed from the active volume, the OTPC will be switched to the state of alert (high sensitivity) and the acquisition system will be triggered opening the CCD exposure for about a second. During this time any decay with emission of heavy charged particles will be recorded. Then, the blocked state will be resumed to wait for the next bunch.

3. Experimental details

The REX-ISOLDE facility offers perfect and unique conditions to perform the ^{6}He decay study with the OTPC detector. The two key factors are the possibility of bunching and well defined energy of reaccelerated particles. This enables preparation of bunches of ^{6}He ions, produced with the on-line mass separator ISOLDE, and then accelerate them with REX linac to the energy of 3 MeV/u and to implant them efficiently within the thin gaseous volume of the OTPC.

The yield of ^{6}He from a UC$_x$ target is given as 4.7 10^{7} per 1 μA of protons on target giving a total yield of up to 10^{8} ions/s for an anticipated 2 μA proton beam. The GPS separator should be used to avoid transmission and charge exchange problems with the RFQ cooler and insufficient low mass-control in the HRS. In order not to suffer from charge exchange in the REXTRAP it is envisaged to do continuous injection into REXEBIS over a low outer trapping barrier. This will be a challenge for the machine since this configuration has a reduced transverse acceptance, small probability for capture in the trap and limited Coulomb force for keeping the charge-bred ^{6}He inside the EBIS due to the maximum charge state of 2^{+}. However, the release time of He (rise time 10 ms, fast fall time 20 ms, and slow fall time 80 ms [13]) implies that a substantial part of the ^{6}He will appear within 100 ms, so we only need an overall efficiency of 10^{-3} in order to get 10^{4} ions/proton bunch as used in the estimate below. Continuous injection into REXEBIS has previously been demonstrated both with stable beams during dedicated tests and with radioactive during an experimental run. With sufficient setup time for testing the injection this should be feasible (note that the beam intensity into REXEBIS is sufficiently high to be measured with ordinary Faraday cups which makes optimization easier). To avoid ^{12}C background in the accelerated beam a stripper foil should be inserted at the end of the Linac to push ^{12}C away from $A/q = 3$.

The bunches of ^{6}He ions will be accelerated to the energy of 3 MeV/u. The OTPC detector will be mounted at the end of the beam line behind a window separating the counting gas from the vacuum. Taking into account the definition of the final energy of ±0.5% and the energy loss and straggling in the vacuum window (100 μm of Al equivalent), we calculate by means of the SRIM code [12] that all ions will be safely stopped in the central part of the active volume of the OTPC detector.

To estimate the expected counting rates, we take the experimental branching ratio for the $\alpha + d$ channel from Ref. [4] and we assume that the shape of the spectrum is given by the model from Ref. [5] which is shown by the solid line in Figure 1. This yields the total branching ratio for the $\alpha + d$ channel (integrated over all energies) of $b_d \cong 2.1 \cdot 10^{-6}$. Then, the probability for a low-energy event ($E_d < 350$ keV, $E_{c.m.} < 525$ keV) equals $0.46 \cdot 10^{-6}$ which is about 20% of the total probability. The OTPC will be switched to the alert state 20 ms after implantation of ions and the exposure will last 1 s. Then, the probability that a decay into the $\alpha + d$ channel occurs (and is observed) during such event equals $0.558 \times b_d = 1.2 \cdot 10^{-6}$. If we assume that 10^{4} ions of ^{6}He are implanted inside the OTPC in one bunch, and that bunches arrive every 5 s, we get the number of 0.012 $\alpha + d$ decays per bunch, and about 200 such decays per day. About 40 of these decays are expected to be low-energy events. Finally, in 5 days we should collect a spectrum statistically equivalent to that of Ref. [4] but extended to the region of lower energies.

Beam Time Request

Finally, we ask for **5 days** (15 shifts) of beam time for the main measurement, and additionally for **1 day** (3 shifts) for setup of ^{6}He injection into REXEBIS and tuning.

References

1. K. Riisager et al., Phys. Lett. B 235, 30 (1990).
2. M. Borge et al., Nucl. Phys. A 560, 664 (1993).
3. D.Anthony et al., Phys. Rev. C 65, 034310 (2002).
4. R. Raabe et al, Phys. Rev. C 80, 054307 (2009).
5. E.M. Tursunov, D. Baye, and P. Descouvemont, Phys. Rev. C 73, 014303 (2006) ; Phys. Rev. C 74, 069904(E) (2006).
6. M. Ćwiok, et al., IEEE Trans. Nucl. Sci. NS-52 (2005) 2895.
7. K. Miernik et al., Nucl. Instr. and Methods A 581, 194 (2007).
8. K. Miernik et al., Phys. Rev. Lett. 99, 192501 (2007).
9. K. Miernik et al. Eur. Phys. J. A 42, 431 (2009).
10. K. Miernik et al., Phys. Rev. C 76, 041304(R) (2007).
11. S. Mianowski et al., Acta Phys. Pol. B 41, 449 (2010).
12. *The stopping and Range of Ions in Matter (SRIM)*, http://www.srim.org .
13. U.C. Bergmann et al., Nucl. Instr. And Meth. In Phys. Res. B 204, 220 (2003).