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Proton decay: spectroscopic probe beyond the proton drip line

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Abstract

Proton decay has been transformed in recent years from an exotic phenomenon into a powerful spectroscopic tool. The frontiers of experimental and theoretical proton-decay studies will be reviewed. Different aspects of proton decay will be illustrated with recent results on the deformed proton emitter ^{135}Tb, the odd–odd deformed proton emitter ^{130}Eu, the complex fine structure in the odd–odd ^{146}Tm nucleus and on excited states in the transitional proton emitter ^{145}Tm.

1. Introduction

The study of nuclear structure far from the line of stability is one of the important facets of contemporary nuclear physics. Nuclei with a negative proton separation energy can spontaneously emit protons. This process is analogous to α decay, but it is intrinsically much simpler since the formation process is not an issue. Proton emission requires quantum tunnelling through the Coulomb and centrifugal barriers. As a result, the proton-decay half-life depends sensitively on the energy and angular momentum of the emitted proton. Consequently, proton-decay rates are sensitive to the angular momentum of the initial and final state. In recent years the study of spontaneous proton emission has been transformed from a curiosity into a powerful spectroscopic tool at the limit of nuclear existence. It has provided a large amount of data on proton Q-values and configurations of many proton emitting states.

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2. Landscape of proton emitters

Around 30 proton emitters with at least one proton decaying state are known to date. The vast majority of them were discovered during the last ten years at Argonne National Laboratory and Oak Ridge National Laboratory, with contributions from Laboratori Nazionali di Legnaro and the University of Jyväskylä. Except for the proton emitting isomeric state in ^{53}Co, all of the known proton emitters are located between $Z = 51$ and $Z = 83$. In fact, only Pr and Pm do not have any known proton emitting isotopes in this region. The known proton emitters span a variety of shapes, from spherical through transitional to oblate and large prolate deformations.

Experimental advances are closely followed by progress in theoretical understanding of different proton decay aspects. The early models treated proton emission from spherical nuclei [1, 2]. Subsequently, the focus turned to the description of the first highly deformed proton emitters ^{131}Eu and ^{141}Ho [3, 4], including the calculation of proton-decay fine structure, i.e. proton decay to the 2^+ excited state in the daughter nucleus [5]. The above calculations were performed in the adiabatic limit, implying infinite moment of inertia of the core. Subsequent calculations used the non-adiabatic approach, essentially including the Coriolis interaction, but did not reproduce observed proton widths very well [6, 7]. This was attributed to the lack of the attenuation of the Coriolis interaction by the pairing interaction. A new approach, which treats the Coriolis interaction and the pairing consistently, was presented recently in [8].

The role of the odd neutron in an odd–odd emitter was elucidated in [9, 10]. Also, the description of spherical and transitional proton emitters was improved by including coupling to core vibrations [11, 12]. Recently, the non-axial degrees of freedom were tackled [13].

3. Theoretical description of proton decay

In order to calculate the proton-decay rate of an odd-Z, even-N nucleus, the single-particle proton wavefunction inside the nuclear potential is matched outside of the nucleus with the outgoing proton Coulomb wave. In a spherical nucleus the initial state has well-defined orbital and total angular momentum, l_p and j_p. In this case the proton-decay width is given by the equation: $\Gamma_{j_p l_p} = \frac{\hbar^2 k}{\mu} \left|N_{j_p l_p}\right|^2 u^2_{j_p l_p}$, where k is the proton wave number, μ is the proton reduced mass, and $N_{j_p l_p}$ is a normalization factor. The $u^2_{j_p l_p}$ coefficient is the probability that the (j_p, l_p) single-particle orbital is empty in the daughter nucleus. The core is assumed to remain unchanged.

In an axially symmetric deformed nucleus, only the projection of the proton angular momentum on the symmetry axis, K_p, is conserved. The proton-decay width is a sum of the widths corresponding to individual spherical single-particle (l_p, j_p) wavefunction components: $\Gamma_{K_p} = \frac{2(2R+1)}{(2I+1)} \sum_{j_p l_p} |\langle j_p K_p R0 | I K_p \rangle|^2 \left|c^{K_p}_{j_p l_p}\right|^2 \Gamma_{j_p l_p} u^2_{K_p}$, where I is the total spin of the initial state and R is the angular momentum of the core. The amplitude of the spherical component (j_p, l_p) in the deformed wavefunction is denoted by $c^{K_p}_{j_p l_p}$. However, only the components which fulfil angular momentum and parity conservation contribute to the total decay width.

In the case of an odd–odd nucleus, although the neutron is only a spectator, it has to be included in the angular momentum balance, which can change the proton-decay rate by allowing additional components in the wavefunction to proton decay.

4. Recent proton-decay experiments at ATLAS

Proton emitters are produced using heavy-ion fusion-evaporation reactions. Typically, the pxn evaporation channels are used. The cross sections vary from tens of μb for the p2n channel

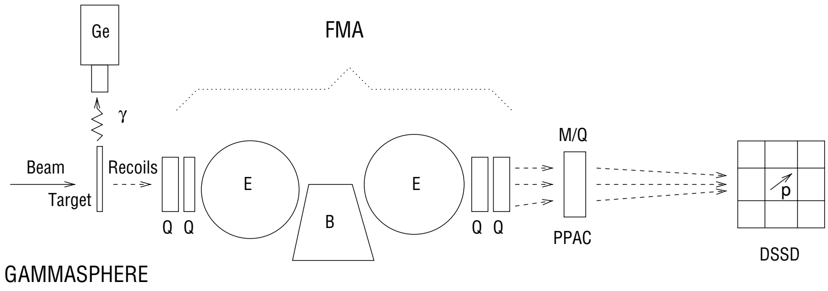

Figure 1. The implantation station at the Argonne Fragment Mass analyzer.

to less than a nb for the p6n channel. Proton emitters are produced in the presence of other much stronger reaction channels. The total fusion-evaporation cross section in the rare-earth region is typically about 500 mb. Thus, a very efficient and selective apparatus is necessary to study proton emitters. A combination of a recoil mass separator with a double-sided Si strip detector (DSSD) has proven to be very effective and has been implemented in several laboratories around the world.

The results shown below were obtained at the ATLAS facility of Argonne National Laboratory. A schematic drawing of the experimental setup is shown in figure 1. The reaction products recoiling from a thin target were separated from the beam and dispersed according to their mass-to-charge state ratio in the Argonne Fragment Mass Analyzer (FMA). After passing through the focal plane, the recoils were implanted into DSSD where they subsequently decayed. The front and back faces of the 60 μm thick DSSD are divided into 80 mutually orthogonal 300 μm wide strips, effectively forming 6400 independent pixels. The implants and the decays were correlated with each other by using spatial and temporal relations. As a result, the mass number, the decay time, and the decay energy were measured for the observed proton decays.

The following paragraphs present a selection of recent results obtained with the FMA, which illustrate current aspects of the proton-decay phenomenon.

4.1. The deformed proton emitter ^{135}Tb

The proton emitter ^{135}Tb is located in the middle of the island of prolate deformation which is intersected by the proton drip line. It is the most recent in a series of highly deformed proton emitters discovered in this region with the FMA. The ^{135}Tb nucleus was produced after evaporation of 1p and 6 neutrons with an estimated cross section of only about 1 nb. A single proton line was observed with an energy of 1179(7) keV, and a half-life of 0.94(+0.33 − 0.22) ms was deduced for the ground state of ^{135}Tb. More details can be found in [14].

The results of calculations using the adiabatic approximation for different prolate deformations are shown in figure 2. The deformation of $\beta_2 \approx 0.33$ is expected for the ^{135}Tb ground state [15]. The calculations agree with the measured half-life only for the $7/2^-[523]$ configuration.

4.2. The odd–odd deformed proton emitter ^{130}Eu

The odd–odd deformed nucleus ^{130}Eu offers a unique opportunity to study the influence of an unpaired neutron on the proton-decay rate. The ^{130}Eu nucleus is calculated to have

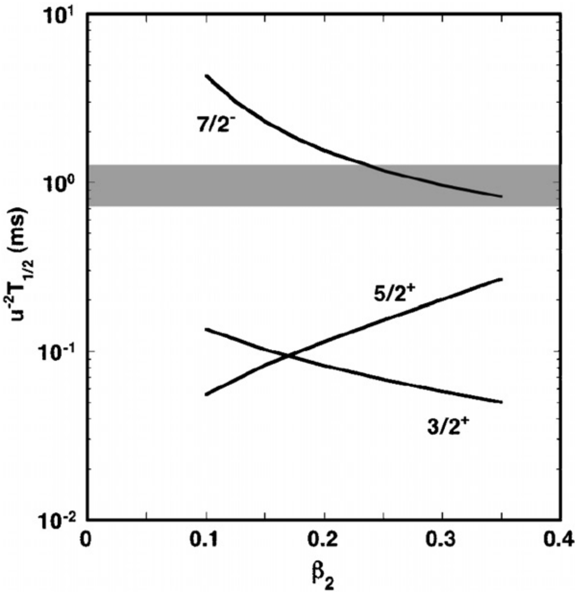

Figure 2. Proton-decay half-lives calculated as a function of quadrupole deformation for ^{135}Tb [14]. The shaded area represents the measured value.

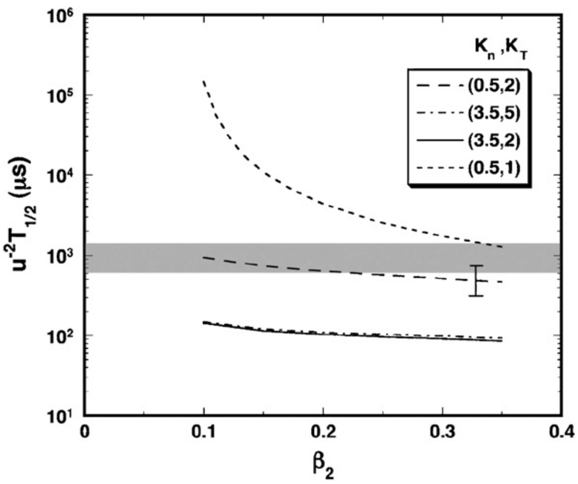

Figure 3. The ^{130}Eu half-life calculated for different combinations of proton and neutron orbitals as a function of quadrupole deformation [10].

prolate deformation of $\beta_2 = 0.32$ [15]. A proton line at 1020(15) keV with a half-life of 0.9(+0.5 − 0.3) ms was assigned to ^{130}Eu [10].

To calculate the proton-decay rate it was assumed that the proton occupies the $3/2^+[411]$ orbital, similar to the ^{131}Eu ground state [3]. The neutron was placed in the $1/2^+[411]$ or $7/2^-[523]$ orbital, which are expected to be located near the Fermi surface. The calculations were performed for both parallel and anti-parallel couplings of the proton and neutron angular momenta. The results of the calculations are shown in figure 3. The best agreement at

$\beta_2 \approx 0.3$ is observed for the K = 1/2$^+$ neutron coupled to the 3/2$^+$ proton. In this case, both couplings give similar results.

4.3. *The odd–odd proton emitter ^{146}Tm*

The proton emitter ^{146}Tm exhibits a complex proton-decay level scheme. At least five proton lines have been associated with this nucleus [16]. An experiment with the GAMMASPHERE Ge array coupled to the FMA was performed to measure prompt γ-ray spectra correlated with the individual ^{146}Tm proton lines. A rotational band feeding the high-spin isomer, which decays via the 1122 keV proton emission, was established. The energies of the transitions in the band are very similar to those of the ground-state band in ^{147}Tm. This suggests that both bands are based on the $h_{11/2}$ proton state and that both nuclei have similar deformation. Gamma-ray spectra associated with other weaker lines were also obtained. The half-lives associated with all five proton lines were measured with higher precision. This allowed to firmly assign the observed lines to three different states (with high, medium and low spin), and to show that one of these states has three proton-decay branches.

4.4. *Excited states in the transitional proton emitter ^{145}Tm*

The calculated deformation changes rapidly from oblate in ^{147}Tm ($\beta_2 = -0.18$) to prolate in ^{145}Tm ($\beta_2 = 0.25$) [15] suggesting softness to triaxial shapes. The ^{145}Tm ground-state decays primarily to the 0$^+$ ground state in the daughter ^{144}Er nucleus. A branch to the 2$^+$ state has been observed recently [17]. The cross section for producing ^{145}Tm is about 200 nb. The ^{145}Tm half-life is only 3 μs.

A regular sequence of mutually coincident γ rays feeding the ^{145}Tm ground state was observed using GAMMASPHERE and FMA. In addition, coincidences between the proton fine structure line and the $2^+ \rightarrow 0^+$ transition in ^{144}Er were detected at the focal plane of the FMA. This is the first time that coincidences between ground-state proton decays and γ rays have been seen. A precise energy of 329(1) keV was measured for the 2$^+$ state in ^{144}Er.

The dominant γ-ray sequence feeding the ground state in ^{145}Tm has properties of a decoupled $\pi h_{11/2}$ band. The $E_\gamma(15/2^- \rightarrow 11/2^-)$ energy, which is close to E(2$^+$) in the even–even core, indicates that the deformation is lower than calculated in ^{145}Tm. The E(19/2$^-$) to E(15/2$^-$) ratio, equivalent to the E(4$^+$)/E(2$^+$) ratio, is about 2.5, which is characteristic of a γ-soft rotor, and is greater than 2.0 for a typical harmonic vibrator, but below the rotor value of 3.33. Also, particle–rotor calculations with an asymmetry parameter $\gamma \approx 30^\circ$ reproduce measured level energies best.

5. Outlook

The full delineation of the proton-drip line between $Z = 50$ and $Z = 82$ is within reach. In many cases, more precise measurements of proton energies, half-lives, fine structure branching ratios and beta-decay branching ratios would be beneficial for comparisons with calculations. The search for new proton emitters below $Z = 50$ and above $Z = 82$ would allow testing of existing proton-decay models for other combinations of single-particle orbitals. However, the narrowing Q-value window accessible experimentally in light nuclei and the competition from fission and alpha decay in heavy systems will present a significant challenge.

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References

[1] Davids C N *et al* 1997 *Phys. Rev.* C **55** 2255
[2] Åberg S, Semmes P B and Nazarewicz W 1997 *Phys. Rev.* C **56** 3011
[3] Davids C N *et al* 1998 *Phys. Rev. Lett.* **80** 1849
[4] Maglione E, Ferreira L S and Liotta R J 1999 *Phys. Rev.* C **59** 589R
[5] Sonzogni A A *et al* 1999 *Phys. Rev. Lett.* **83** 1116
[6] Esbensen H and Davids C N 2001 *Phys. Rev.* C **63** 014315R
[7] Kruppa A T, Barmore B, Nazarewicz W and Vertse T 2000 *Phys. Rev. Lett.* **84** 4549
[8] Fiorin G, Maglione E and Ferreira L S 2003 *Phys. Rev.* C **67** 054302
[9] Ferreira L S and Maglione E 2000 *Phys. Rev. Lett.* **84** 4549
[10] Davids C N *et al* 2004 *Phys. Rev.* C **69** 011302(R)
[11] Davids C N and Esbensen H 2001 *Phys. Rev.* C **64** 034317R
[12] Hagino K 2001 *Phys. Rev.* C **64** 041304(R)
[13] Davids C N and Esbensen H 2004 *Phys. Rev.* C **69** 034314
[14] Woods P J *et al* 2004 *Phys. Rev.* C **69** 051302(R)
[15] Möller P, Nix J R, Myers W D and Światecki W J 1995 *At. Data Nucl. Data Tables* **59** 185
[16] Ginter T N *et al* 2003 *Phys. Rev.* C **68** 034330
[17] Karny M *et al* 2003 *Phys. Rev. Lett.* C **90** 012502