ANL/PHY/CP-98432

Deformed Proton Emitters

A.A. Sonzogni, C.N. Davids, D. Seweryniak, M.P. Carpenter, D.J. Henderson, R.V.F. Janssens, T. Lauritsen, P. Reiter, J. Schwartz, J. Uusitalo, I.L. Wiedenhöver

Argonne National Laboratory

P.J. Woods, T. Davinson

University of Edinburgh

J.J. Ressler, W.B. Walters

University of Maryland

J.A. Cizewski, N. Fotiades

Rutgers University

RECEIVED
OCT 13 1999
OSTI

(February 8, 1999)

Abstract

The mechanisms of proton radioactivity from deformed rare earth nuclei are discussed and preliminary results on the fine structure decay of ^{131}Eu are presented.

Since it was first reported in 1982, ground-state proton radioactivity has become one of the most exciting areas in Nuclear Physics [1]. Its relatively late discovery, many years after alpha radioactivity and a mere couple of years before cluster decay, indicates the difficulties associated with its study. Unlike alpha radioactivity, where it is possible to find alpha emitters even in the valley of stability, proton radioactivity happens for very neutron deficient nuclei, for which production cross sections are often smaller than a few tens of μb, even with the most proton rich targets and projectiles.

In essence, the proton emission probability is the product of two terms. One takes into account the tunneling probability, while the other -often referred to as spectroscopic factor - represents the overlap between parent and daughter wave functions. For nuclei with nearly spherical shapes, the total potential can be taken as spherically symmetric and the proton angular momentum is conserved. Several methods to calculate the tunneling probability and the spectroscopic factors have been developed with considerable success [2], [3]. Since the proton half-life depends strongly on the amount of angular momentum carried away, proton radioactivity in spherical nuclei is an excellent spectroscopic tool, allowing one to determine spin and parity of the parent nuclei. There are, however, two exceptional cases, ^{113}Cs and ^{109}I, whose half-lives can not be accounted for with these methods. Since these nuclei are predicted to have a modest but nevertheless non-zero quadrupole deformation - $\beta_2 \sim 0.15$ [4] - it was suspected that calculating the half-lives under the assumption that they had spherical shapes wouldn't work. This lead Bugrov and Kadmensky [5] to develop a formalism for proton radioactivity from deformed nuclei. In this model, the half-life depends on the wave function structure of the Nilsson orbital, and it is in some cases possible to determine the Nilsson orbital from which the emitted proton originated.

When the nucleus has a permanent deformation - for instance prolate - the potential that the proton feels is no longer spherically symmetric. Deep inside the nucleus as well as at large distances, the potential is mostly spherical; but at the nuclear surface, the potential at the poles can be quite different from the potential in the equator. In other words, the non-spherical terms of the potential peak near the nuclear surface. In addition, the proton orbital angular momentum is no longer a good quantum number; in fact, the wave function is often written as a sum of spherical components with different values of J and ℓ. As a consequence, during the tunneling process as the proton crosses the nuclear surface, its angular momentum can change due to the interaction with the non-spherical terms.

The rare earth proton emitters have been under close scrutiny lately [6,8] since they are expected to be in a region of large values of deformation ($\beta_2 \sim 0.3$). The nuclei ^{131}Eu and ^{141}Ho are of special interest since they have been shown to be highly deformed [6]. Their half-lives could not be explained under the assumption that they were spherical in shape, but could be understood in terms of the formalism of Bugrov and Kadmensky [6]. New results on the decay of ^{131}Eu are presented in this contribution. Since the experiment was performed only a few months ago, readers should understand that this is a work in progress and that the results presented are preliminary.

The experiments were carried out at Argonne National Laboratory. A 402 MeV ^{78}Kr beam from ATLAS was used to bombard a 0.77 mg/cm^2 ^{58}Ni foil with an intensity of $\sim$ 2.5 pnA. Details of the experimental technique can be found elsewhere [6]; a brief description is given below. The FMA [9] was used to select the reaction products of interest (mass 131). At the focal plane of the FMA, a PGAC detector was used to obtain position and timing information. A 65 μm thick, 48x48 strip Double Sided Silicon Detector (DSSD) was placed 40 cm downstream of the PGAC. The combined use of PGAC and DSSD allows for two different kind of events; an implant, when both PGAC and DSSD fire together, and a decay, when only the DSSD produces a signal. The time difference between a recoil and an implant was recorded, from which the half-lives of the different decay events can be determined. In order to veto out events that didn't leave their full energy in the DSSD, a Si detector was placed behind the DSSD, while 4 Si detectors in a box geometry were placed before it. The calibration and gain matching of the DSSD were done with standard alpha sources and protons from ^{147}Tm. A 4.6 mg/cm^2 thick Ni foil was placed just before the DSSD acting as a degrader during some of the runs.

A proton energy spectrum is shown in fig. 1. It corresponds to a maximum time difference between A=131 implants and proton decay of 100 ms. A very similar spectrum was seen when ^{131}Eu was discovered, but with far fewer counts. With the higher level of statistics available now, a second peak can be seen with $\sim$ 120 keV less energy than the main peak. The half life for these two proton peaks is around 20 ms. Since the proton half-life depends quite strongly on the proton energy, the fact that two proton peaks with an energy difference of $\sim$ 120 keV exhibit the same half-life is a clear indication that this is an unusual situation that goes beyond what was observed with spherical proton emitters.

As it has been argued before, we can expect that of the M=131 isobars implanted in the DSSD, only Eu will proton decay since the other ones - in particular the near neighbors ^{131}Gd and ^{131}Sm - are expected to be proton bound. The fact that both proton lines have similar half-lives suggests that they both originate from the same state in the parent nucleus ^{131}Eu, but end up in two different states. Keeping in mind that the quadrupole permanent deformation of the daughter nucleus - ^{130}Sm - is predicted to be 0.3 - 0.35 [4], [10], the energy of the 2^+ state of the ground state rotational band will lie in the 110-140 keV range. It is not difficult then to theorize that the higher energy proton feeds the ground state of ^{130}Sm while the lower one feeds the 2^+ state. In other words, we think that this is the first observed case of fine structure in proton radioactivity.

From the energy spectrum one can define the measured branching ratios for the 2^+ state and ground state ($b_{2^+}^{exp}$ and $b_{g.s}^{exp}$) as the ratio of the individual peak areas to the sum of the peak areas. The 2^+ state can decay either by gamma-ray emission or internal conversion. In the latter case, the proton and the electron can be detected simultaneously and the energy of the event will be distributed between the 2^+ peak and the ground state peak. One then concludes that there can be events that decayed to the 2^+ state, but are observed as decays to the ground state. Therefore, the values of $b_{2^+}^m$ and $b_{g.s.}^m$ can be different from the true or intrinsic values of branching ratio (b_{2^+} and $b_{g.s.}$). The correction factor that will bring the measured values to the intrinsic one can be calculated with a MonteCarlo simulation, which has to take into account: a) the implantation of the ^{131}Eu atoms in the Si detector b) the proton emission c) the subsequent gamma or electron emission if the 2^+ state was populated

c) the response of the detector. The most important parameters in the simulation are the kinetic energy of the ^{131}Eu atom, the thickness of the DSSD, the energy of the 2^+ state and its internal conversion coefficient.

The measured energy of the 2^+ is 120 keV, leading to an internal conversion coefficient of 1.23 [11]. Under the conditions that the experiment was run, the simulation indicates that $b^m_{2^+}$ is a factor of 1.5 smaller than b_{2^+}. Combining all the results together, a branching ratio for the 2^+ state of (14.4±4.1)% was obtained.

In what follows, the formalism developed by Kadmensky and Bugrov [5] is used to explain the experimental results. Briefly, the wave function for a single proton is expanded in term of spherical wave functions:

$$\Psi(N\Omega) = \sum_{j\ell} C_{j\ell}(N\Omega)|N\ell j\Omega > . \tag{1}$$

The transition amplitude between an initial state (J_i, K_i) and a final state (J_f, j_p, ℓ_p) is given by:

$$B^{J_iK_i}_{J_fj_p\ell_p} = (\frac{2(2J_f+1)}{2J_i+1})^{1/2} < J_fj_p0K_i|J_iK_i > U^2 \sum_{\ell j,m_s} C_{\ell j}(N\Omega) < \ell_p\frac{1}{2}(K_i-m_s)m_s|j_pK_i >$$
$$< \ell\frac{1}{2}(K_i-m_s)m_s|jK_i >< Y^{K_i-m_s}_{\ell_p}(\Omega')\frac{F_{\ell_p}(k,\eta,r)}{r}|V(\vec{r})|\frac{R_{N\ell j}(r)}{r}Y^{K_i-m_s}_{\ell}(\Omega') >, \tag{2}$$

where U^2 is the spectroscopic factor, $F_{\ell_p}(k,\eta,r)$ is the regular Coulomb wave function, $\frac{R_{N\ell j}(r)}{r}$ is the radial part of $|N\ell j\Omega >$ and V is the sum of the nuclear potential plus the non-spherical component of the Coulomb potential. The corresponding decay width is:

$$\Gamma^{J_iK_i}_{J_fj_p\ell_p} = 2\pi|B^{J_iK_i}_{J_fj_p\ell_p}|^2. \tag{3}$$

The decay width for a proton feeding the ground state is given by:

$$\Gamma_{0^+} = \Gamma^{J_iK_i}_{J_f=0^+j_p\ell_p}. \tag{4}$$

On the other hand, if the proton feeds the 2^+ state:

$$\Gamma_{2^+} = \sum_{j_p\ell_p} \Gamma^{J_iK_i}_{J_f=2^+j_p\ell_p}. \tag{5}$$

The total decay width is:

$$\Gamma = \Gamma_{0^+} + \Gamma_{2^+}, \tag{6}$$

and the half-life:

$$t_{1/2} = ln(2)\hbar/\Gamma. \tag{7}$$

The branching ratios are given by:

$$b_{0^+} = \Gamma_{0^+}/(\Gamma_{0^+} + \Gamma_{2^+}) \tag{8}$$

$$b_{2^+} = \Gamma_{2^+}/(\Gamma_{0^+} + \Gamma_{2^+}) \tag{9}$$

In equation 2, the key ingredients are the values of the $C_{j\ell}(N\Omega)$ coefficients and the nuclear potential systematics used. In this case, the $C_{j\ell}(N\Omega)$ were calculated using the formalism of ref. [12], while the Becchetti-Greenlees systematics of the nuclear potential [13] was used.

The results of our calculation compared with the experimental values of branching ratio can be seen in fig. 2. As it was mentioned in ref. [6], the orbitals $3/2^+[411]$ and $5/2^+[413]$ lie very close to the Fermi surface in Eu isotopes. The calculated half-lives for each orbital are close enough to the measured values so that none could be preferentially chosen over the other. The branching ratio, however, provides more information. As can be seen from the figure, only the calculations from the $3/2^+[411]$ orbital are in close agreement with the measured values.

In order to understand why each orbital gives such a different value of branching ratio, it is necessary to inspect more closely the wave function structure of each orbital. For $3/2^+[411]$, the $d_{3/2}$ component represents $\sim 4\%$ of the wave function, the $d_{5/2}$ takes $\sim 60\%$ and the higher angular momentum components account for the rest. On the other hand, for $5/2^+[413]$, the $d_{5/2}$ term accounts for only $\sim 1\%$ and the rest goes to higher angular momentum terms. As a consequence, for the $3/2^+[411]$ orbital, a considerable fraction of Γ_{2^+} originates from the $d_{5/2}$ term since it has the same value of angular momentum -and therefore the same centrifugal barrier- as the $d_{3/2}$. For $5/2^+[413]$, however, the components of the wave function other than the $d_{5/2}$ have higher values of orbital angular momentum and therefore don't make a considerable contribution to Γ_{2^+}.

^{141}Ho is another nucleus which may also show fine structure in its proton radioactivity. From an experiment performed to study its excited states, there are hints indicating that this may be the case [14]. However, it may be necessary to wait until an experiment optimized for the search of the weaker decay to the 2^+ states takes place before quantitative results can be obtained.

In summary, with a higher-statistics experiment to study of the proton decay of ^{131}Eu, it was possible to observed the decay to the 2^+ of the rotational band. Through he comparison between experimental and calculated values of branching ratios, the ground state of ^{131}Eu was assigned to the $3/2^+[411]$ Nilsson orbital.

Acknowledgements:

We would like to thank the organizers of this meeting for inviting us to an excellent conference which took place in a wonderful location. We wish Prof. Ramayya many more happy birthdays.

This work was supported by the U.S. Departmnet of Energy, Nuclear Physics Division, under Contract No. W-31-109-ENG-38.

REFERENCES

[1] P.J. Woods and C.N. Davids, Annu. Rev. Nucl. Part. Sci **47**, 541 (1997).

[2] C.N. Davids *et al*, Phys. Rev. Lett. **76**, 592 (1996).

[3] S.Aberg, P.B. Semmes and W. Nazarewics, Phys. Rev **C56**, 1762 (1997), Phys. Rev. **C58**, 3011 (1998).

[4] P. Möller *et al*, At. Data Nucl. Data Tables **59**, 185 (1995).

[5] V.P. Bugrov and S.G. Kadmensky, Sov. J. Nucl. Phys. **52**, 229 (1990), S.G. Kadmensky and V.P. Bugrov, Phys. Of At. Nuclei **59**, 399 (1996).

[6] C.N. Davids *et al*, Phys. Rev. Lett. **80**, 1849 (1998).

[7] D. Seweryniak *et al*, Phys. Rev. **C55**, R2137 (1997).

[8] J.C. Batchelder *et al*, Phys. Rev. **C57**, R1042 (1998).

[9] C.N. Davids *et al*, Nucl. Instrum. Methods Phys. Res., Sect B **70**, 358 (1992).

[10] Y. Aboussir *et al*, At. Data Nucl. Data Tables **61**, 127 (1995).

[11] F. Rösel, H.M. Fries, K. Alder and H.C. Pauli, At. Data and Nuc. Data Tables, **21**, 91 (1978).

[12] B.L. Andersen, B.B. Back, and J.M. Bang, Nucl. Phys. **A147**, 33 (1970).

[13] F.D. Becchetti and G.W. Greenlees, Phys. Rev. **182**, 1190 (1969).

[14] D. Seweryniak *et al*, to be published.

FIGURES

FIG. 1. Energy spectrum from the proton decay of residues with mass 131

FIG. 2. Branching ratio for the 2^+ state. The full lines correspond to calculations as described in the text. The experimental value lies in the band between the dashed lines

Fig. 1

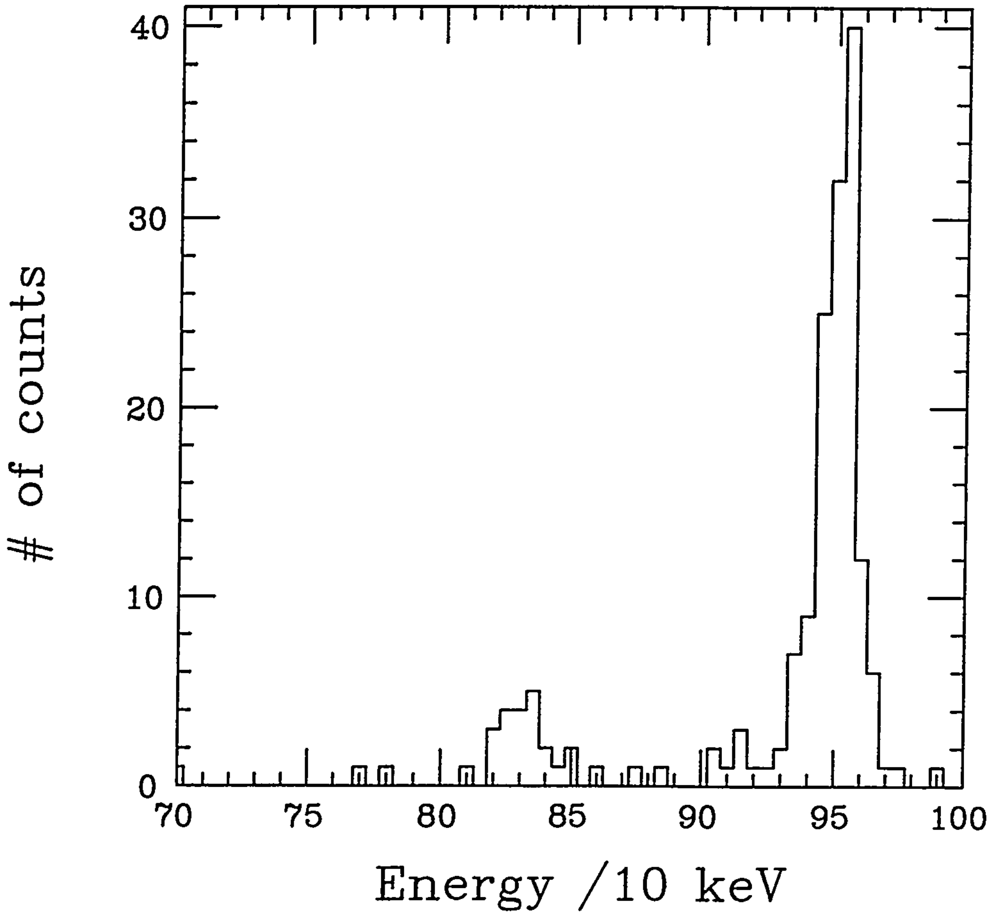
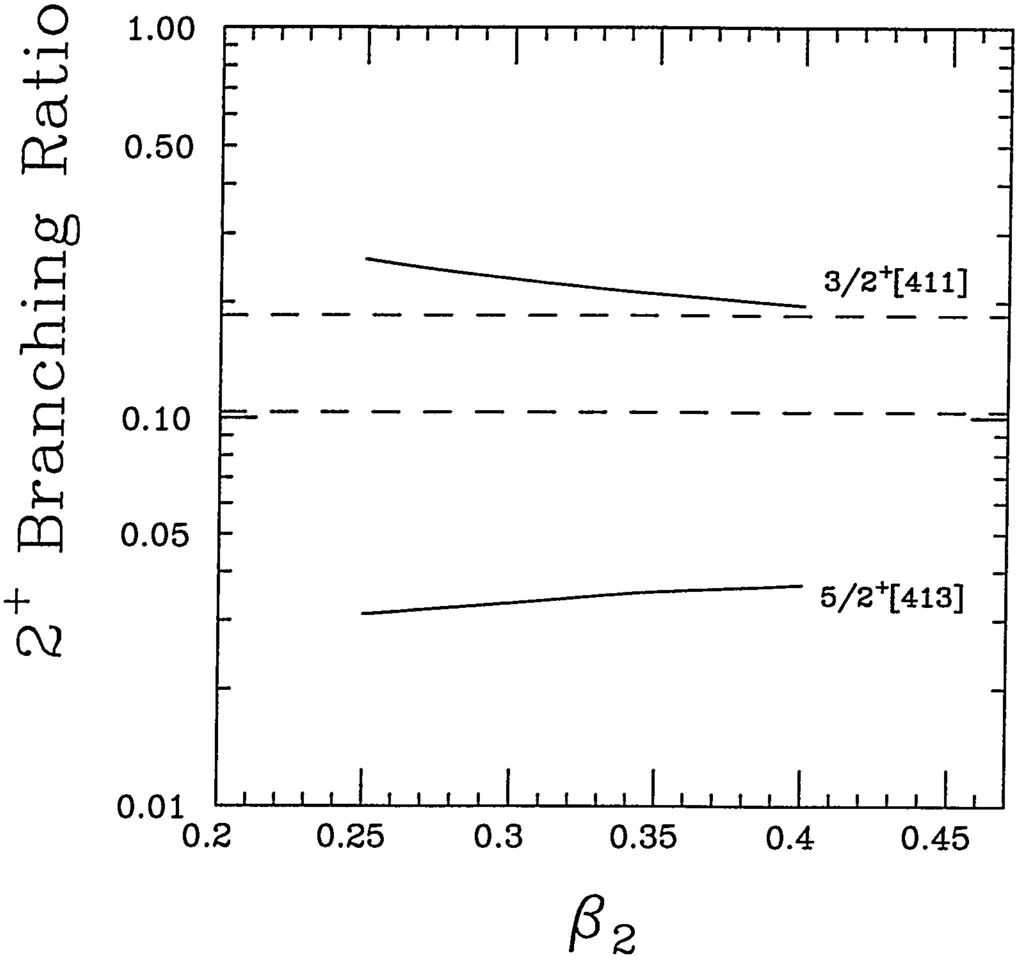


Fig. 2


2+ Branching Ratio
1.00
0.50
0.10
0.05
0.01
0.2
0.25
0.3
0.35
0.4
0.45
β_2
3/2+[411]
5/2+[413]