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Beta-decay to the proton halo state in ^{17}F

M.J.G. Borge¹, J. Deding², P.G. Hansen³, B. Jonson⁴,
G. Martínez Pinedo⁵, P. Møller³, G. Nyman⁴,
A. Poves⁵, A. Richter⁶, K. Riisager³, O. Tengblad²
and the ISOLDE collaboration

1. Insto. de Estructura de la Materia, CSIC, Serrano 119, E-28006 Madrid
2. PPE Division, CERN, CH-1211 Genève 23
3. Institut for Fysik og Astronomi, Aarhus Universitet, DK-8000 Aarhus C
4. Fysiska Institutionen, Chalmers Tekniska Högskola, S-412 96 Göteborg
5. Depart. de Fisica Teorica, Univ. Autonoma de Madrid, E-28049 Madrid
6. Institut für Kernphysik, Technische Hochschule, D-6100 Darmstadt

Abstract

In the first experiment at the newly constructed ISOLDE Facility the first-forbidden beta-decay of ^{17}Ne into the first excited state of ^{17}F has been measured. It is a factor two faster than the corresponding mirror decay and thus gives one of the largest recorded asymmetries for beta decays feeding bound final states. Shell-model calculations can only reproduce the asymmetry if the halo structure of the ^{17}F state is taken into account.

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Most experimental studies of nuclear halo states (states where one or more nucleons have a spatial distribution that extends far beyond the nuclear core) have so far been done by means of nuclear reactions, see e.g. the reviews in [1]. The only exceptions we are aware of are the determination of ground state properties of ^{11}Li by atomic beam techniques [2] and the survey of beta-decay properties of the heavy He and Li isotopes [3]. We present here an experiment on beta-decay into a proton halo state in which an abnormal decay rate (relative to the mirror decay) is found.

A recent general study of two-body halos [4] showed that well developed neutron halos can occur only for relative s- and p-waves. Proton halos are hampered by the additional Coulomb barrier and can be expected only for core charges less than about 10. There are thus rather few possible proton halo states. The at present best established one, and the one we have chosen to study here, is the first excited state in ^{17}F at 495 keV, bound with respect to the $^{16}\text{O}+p$ threshold by only 105 keV, see figure 1. This state is well described as a ^{16}O core surrounded by an s-wave proton [5]. The Coulomb barrier will tend to confine the proton to the core, but the charge is still not sufficient to do this efficiently [4] and the loosely bound proton will spend an appreciable time at larger distances. Even though this takes place in an excited state several experiments have already shown the presence of the halo. One of the best probes of the wavefunction at large relative distances between core and halo particle is the direct radiative proton (or neutron) capture; in the case of capture on ^{16}O the main contribution at low energies comes from several tens of fm [6] and the data confirm the presence of a large tail. Another experimental verification comes from the E2-transition between the first excited state and the ground state. This can only be reproduced when wavefunctions that take the small binding energy into account are used [7, 8].

The beta-decay of ^{17}Ne into states in ^{17}F has been studied several times [9, 10], but the experiments have so far focussed on the beta-delayed charged particles. The transitions to the two bound states are first-forbidden and are therefore not prominent. The strength of the transition to the first excited state has been calculated [11] assuming strict mirror symmetry with the corresponding decay of ^{17}N into the first excited state of ^{17}O . The essential parameter is the ratio f^+/f^- for the two mirror transitions; calculations with different wavefunctions gave values in the range 11–12. The partial half-life for the ^{17}N transition [12] of 139 ± 23 s gives then a predicted partial half-life for the ^{17}Ne transition, that combined with the ^{17}Ne total half-life [10] of 109.3 ± 0.6 ms yields a predicted branching ratio for the ^{17}Ne decay of $f^+/f^- \times (7.9 \pm 1.3) \cdot 10^{-4}$, i.e. around 0.9 %.

We have studied the beta-decay of ^{17}Ne at the ISOLDE facility at CERN, now operating at the PS Booster (PSB) [13, 14]. The activity was produced by 1 GeV protons hitting a magnesium oxide target and was through a cooled line fed to a plasma ion source. The ions were accelerated and after mass separation directed to the experimental set-up. The Ne ion beam was kept at 8000 ions/s and collected in a thin aluminium foil facing a Si surface barrier detector for charged particle detection. A Ge detector recorded the gamma spectrum and a plastic scintillator recorded beta particles as shown in figure 1. The solid angle of the Si detector was $(9.1 \pm 0.4) \cdot 10^{-3}$ and the total efficiency of the Ge detector at 495 keV, including the solid angle, was determined to be $(4.3 \pm 0.3) \cdot 10^{-3}$ by use of standard calibration gamma sources. Singles as well as beta-coincident gamma and charged particle spectra were recorded and later analyzed off-line.

A secondary beam of ^8He was used to cross-check the efficiencies. All decays of ^8He leading to particle bound levels go to the first excited state in ^8Li with a total branching

Figure 1: Partial decay scheme and experimental set-up. The Ne^+ beam is led through an Al collimator and collected on an Al foil that is seen by the three detectors: a plastic scintillator for beta particles, a Si detector for protons and a Ge detector for gamma rays.

ratio [15] of 84 %. This state decays by emission of a 981 keV gamma ray to the ground state of ^8Li that subsequently beta decays with a half life of 0.84 s. All levels fed in ^8Be break up into two alpha particles, so that there is one 981 keV gamma ray per two alpha particles. The alpha particle spectrum of ^8Be listed in [16] was used as reference (there are no line structures in this spectrum) and we could thus check the relative efficiency of the gamma and charged particle detectors. The value determined from the ^8He decay agrees within uncertainties with the value determined from the calibration sources.

The experimental gamma spectrum recorded from ^{17}Ne is shown in figure 2. The spacing between the pulses from the PSB synchrotron is in the range of seconds, which allows the half-life of the activity to be checked without any loss of beam. All spectra recorded are consistent with the known half-life of 109.3 ms and, as can be seen in figure 2, no activity remains one second after proton impact. The only gamma rays present in the beta-coincident spectra are the 511 keV positron annihilation gamma ray and the 495 keV gamma line from the decay of the first excited state in ^{17}F , whereas some background lines are seen in the singles spectra. The charged particle spectra agree with the ones measured earlier [10] and give the total activity of ^{17}Ne after the small correction for the decays that go to the lowest two states in ^{17}F . The branching ratio for decays to the first excited state can therefore be extracted from the ratio of the number of counts in the 495 keV line to the number of counts in the charged particle spectrum. Both the beam collimators and the shielding between the collimator and the Ge detector were varied to assure that only the activity on the collection foil was seen by the detectors. The results of all these tests agreed, as did the results from singles and beta-coincident spectra. The final value for the branching ratio is $(1.65 \pm 0.16) \%$.

We first put this result in perspective by comparing with other mirror beta-decays. This is a well-known procedure for isolating binding energy (and Coulomb) effects in beta decays, see e.g. [17]. Decays are normally compared by constructing the quantity

$$\delta = \frac{(ft)^+}{(ft)^-} - 1,$$

Table 1: Mirror beta-decay asymmetries, bound final states.

Decays β^-, β^+	T	E* MeV	log(ft) β^-, β^+	δ	Ref. ^a
allowed transitions					
$^{12}\text{B} \rightarrow ^{12}\text{C} \leftarrow ^{12}\text{N}$	1	0.0	4.07, 4.12	0.129(8)	[22]
	1	4.44	$\begin{cases} 5.15, 5.15 \\ 5.12, 5.15 \end{cases}$	$-0.001(14)$ 0.066(18)	[23] [24]
$^{13}\text{B} \rightarrow ^{13}\text{C}, ^{13}\text{N} \leftarrow ^{13}\text{O}$	3/2	0.0, 0.0	4.03, 4.08	0.11(3)	[25]
$^{18}\text{O} \leftarrow ^{18}\text{F} \leftarrow ^{18}\text{Ne}$	1	0.0	3.55, 3.10	0.045(11)	
$^{20}\text{F} \rightarrow ^{20}\text{Ne} \leftarrow ^{20}\text{Na}$	1	1.63	4.97, 4.99	0.038(22)	[26]
$^{24}\text{Na}^m \rightarrow ^{24}\text{Mg} \leftarrow ^{24}\text{Al}^m$	1	0.0	5.80, 5.68	-0.2(3)	
$^{28}\text{Al} \rightarrow ^{28}\text{Si} \leftarrow ^{28}\text{P}$	1	1.78	4.86, 4.85	-0.03(5)	
$^{30}\text{Si} \leftarrow ^{30}\text{P} \leftarrow ^{30}\text{S}$	1	0.0	4.84, 4.33	-0.08(3)	
first-forbidden transitions					
$^{17}\text{N} \rightarrow ^{17}\text{O}, ^{17}\text{F} \leftarrow ^{17}\text{Ne}$	3/2	0.87, 0.50	6.80, 6.37	-0.55(9)	this work

^a The data are taken from the compilations [12, 20, 21] and the listed references.

Table 2: Mirror beta-decay asymmetries, unbound final states, allowed transitions.

Decays β^-, β^+	T	E* MeV	Γ^a keV	log(ft) β^-, β^+	δ	Ref. ^b
$^8\text{Li} \rightarrow ^8\text{Be} \leftarrow ^8\text{B}$	1	2.94	1500	$\begin{cases} 5.37, 5.43 \\ 5.72, 5.77 \end{cases}$	0.14(2)	[27] [16]
$^9\text{Li} \rightarrow ^9\text{Be}, ^9\text{B} \leftarrow ^9\text{C}$	3/2	0.0, 0.0	-, 0.5	5.32, 5.27	-0.09(16)	[28]
	3/2	2.43, 2.36	0.8, 81	5.13, 5.49	1.2(5)	[28]
$^{12}\text{B} \rightarrow ^{12}\text{C} \leftarrow ^{12}\text{N}$	1	7.65	0.009	4.13, 4.34	0.6(4)	
	1	10.3	3000	4.2, 4.36	0.4(9)	
$^{13}\text{B} \rightarrow ^{13}\text{C}, ^{13}\text{N} \leftarrow ^{13}\text{O}$	3/2	3.68, 3.50	-, 62	4.45, 4.55	0.26(30)	
	3/2	7.55, 7.38	-, 75	5.33, 5.56	0.7(9)	
	3/2	8.86, 8.92	-, 230	4.59, 4.66	0.17(36)	
	3/2	9.90, 9.48	-, 30	4.95, 5.09	0.4(6)	
$^{17}\text{N} \rightarrow ^{17}\text{O}, ^{17}\text{F} \leftarrow ^{17}\text{Ne}$	3/2	4.55, 4.65	40, 225	4.41, 4.58	0.47(8)	[10]
	3/2	5.39, 5.49	28, 68	3.86, 3.81	-0.10(4)	[10]
	3/2	5.95, 6.04	32, 30	4.35, 4.55	0.58(12)	[10]
$^{21}\text{F} \rightarrow ^{21}\text{Ne}, ^{21}\text{Na} \leftarrow ^{21}\text{Mg}$	3/2	4.53, 4.29	-, 4	5.03, 4.82	-0.38(5)	[29]
	3/2	4.68, 4.47	-, 21	4.52, 4.48	-0.09(8)	[29]

^a States stable towards particle emission are denoted by a dash.

^b The data are taken from the compilations [12, 20, 21] and the listed references.

Figure 2: A section of the beta-coincident gamma-ray spectrum from the decay of ^{17}Ne . The ordinate is the recorded number of counts per 340 eV, the spectrum corresponds to 6% of the total statistics. The arrow marks the 495 keV line from $^{17}\text{F}(\frac{1}{2}^+)$, the peak at 511 keV is from positron annihilation. The full line is the spectrum taken in the first second after proton impact on the ISOLDE target, the dashed line the spectrum taken in the subsequent three seconds.

which will be zero when complete symmetry is present. The known mirror beta-decays are listed in tables 1 and 2 for bound and unbound final states, respectively. Only transitions with low $\log(ft)$ values (< 6 for allowed transitions) are included in the tables. In transitions with larger $\log(ft)$ the low decay rate could be due to accidental cancellations in the matrix element which would result in an abnormal sensitivity to small changes in the wavefunction. Binding effects could then show up strongly but would be hard to analyze quantitatively. This seems to happen for the mass 14 and 32 multiplets as discussed in [18]. (Note that the asymmetry in the mass 24 multiplet still could be reproduced theoretically in a shell-model calculation that included the Coulomb interaction and thus took the binding energy effects into account explicitly [19].) The asymmetries are typically less than 0.1 for bound final states, but appreciably larger for unbound final states. They tend in both cases to be positive, i.e. the β^- decay is faster than the corresponding β^+ decay.

The transition to the first excited state in ^{17}F is first-forbidden and has a fairly large $\log(ft)$ value. Our measured branching ratio is clearly larger than the one expected if mirror symmetry prevailed. The asymmetry is exceptionally large compared to the allowed bound final state decays and rather like the ones seen for unbound final states. This is consistent with the large asymmetry being caused by the presence of the halo, as the halo wavefunction is intermediate between the ones of strongly bound states and continuum states. Note, however, that the β^+ decay is fastest in our case.

For a more quantitative explanation of the results we have performed shell-model calculations. These are an extension of the calculations of Towner and Hardy [11], for definiteness only the configuration mixing wavefunctions (ZBM) [30] have been used here.

Figure 3: The ratio of f-values, f^+/f^- , calculated for the first-forbidden transitions from ^{17}Ne and ^{17}N using $b_0=1.85$ fm. See the text for details. The experimental value of the ratio is 21 ± 4 .

With the prescription of Millener et al. [31] and assuming mirror symmetry we obtain a ratio of f-values of $f^+/f^- = 9.6$. This corresponds to a predicted branching ratio of $(0.75 \pm 0.12) \%$. The experimental branching ratio is larger and thus gives the final δ -value of -0.55 ± 0.09 listed in the table.

The following elements are now introduced in order to improve upon the model calculations. First the single particle energies of the $2s_{1/2}$ proton and neutron orbits are adjusted to fit the actual excitation energies. In this way the Thomas-Ehrman shift [5] is taken explicitly into account. A harmonic oscillator basis was used to calculate the single particle matrix elements. Their size parameters are allowed to vary for the three relevant orbits, namely b_0 for the $1p_{1/2}$ orbit, b_ν for the $2s_{1/2}$ neutron orbit and b_π for the $2s_{1/2}$ proton orbit.

The dependence of the ratio f^+/f^- on the size parameters for the $2s_{1/2}$ orbits is illustrated in figure 3. To fit the experimental data the ratio should be 21 ± 4 , which only is obtained if b_π is larger than b_ν . The value of the Thomas-Ehrman shift furthermore implies that the effective size parameter b_π has to be larger than the effective b_ν by 0.5–0.6 fm. Several reasonable sets of size parameters are seen to exist that are compatible with both the beta decay asymmetry and the Thomas-Ehrman shift. As a specific example the values $b_0=1.85$ fm, $b_\nu=1.95$ fm and $b_\pi=2.55$ fm give $f^+/f^-=19.3$ and correspond to a radius for the $2s_{1/2}$ proton orbit of 4.9 fm, consistent with the proton halo picture.

We assumed implicitly that the $2s_{1/2}$ neutron orbit is the same in ^{17}N and ^{17}O and similarly that the $2s_{1/2}$ proton orbit is the same in ^{17}Ne and ^{17}F . This hypothesis may be criticized because the separation energies in ^{17}Ne ($S_p=1.49$ MeV and $S_{2p}=954$ KeV) are not small enough to produce a proton halo. However, the $2s_{1/2}$ proton orbit is only a small component of the ^{17}Ne ground state, the configuration $(1p_{1/2})^{-\nu}(2s_{1/2})^{2\pi}$ represents only 10 % while the configuration $(1p_{1/2})^{-\nu}(1d_{5/2})^{2\pi}$ attains 50 %. Consequently even if the size of the ground state of ^{17}Ne were normal, the $2s_{1/2}$ orbit could still be quite extended. If b_π was allowed to differ for the $2s_{1/2}$ orbits in ^{17}Ne and ^{17}F the spatial overlap between these orbits should then also be included. This would give a reduction of the decay rate, but it would clearly still be possible to fit the data with reasonable parameter values. One might also worry about the asymptotic tail of the wavefunction that cannot

be reproduced correctly with a restricted harmonic oscillator basis. This is not a problem as long as the behaviour close to the nuclear core is correct. (The single particle matrix elements are only sensitive to the region up to 8 fm.) Use of a Woods-Saxon potential would therefore not change our conclusions.

In summary, we have measured the first-forbidden decay of ^{17}Ne into the first excited (halo) state in ^{17}F and by comparison with the mirror decay found a pronounced asymmetry. This could be understood quantitatively within a model (ZBM) that gives a fair description of the spectroscopic properties of nuclei around ^{16}O . Put briefly, the asymmetry arises due to the unusually large spatial extent of the proton $2s_{1/2}$ orbit. Halos have thereby been shown to affect beta decay rates directly.

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