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Candidates for electron-neutrino mass measurements:

The case of ^{81}Kr

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Abstract

The nuclear data of the known candidates for neutrino mass determination by resonant electron-capture beta decay are reviewed. New results are presented for the isotope ^{81}Kr , where the transition to the 276 keV state has been found to have $Q_{\text{EC}} = 4.7 \pm 0.5$ keV and a branching ratio of $(3.0 \pm 0.2) \cdot 10^{-3}$.

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It has been suggested [1, 2] that the spectrum of radiations following electron-capture (EC) beta decay under special conditions offer a very sensitive method for probing the electron neutrino mass. To see why this is so, consider the following arguments: (i) EC gives predominantly neutrinos of energy $Q_{EC} - B_{ns}$, where Q_{EC} is the energy release corresponding to the $^{81}\text{Kr} - ^{81}\text{Br}$ mass difference and B_{ns} is an s-state binding energy. (ii) Experimentally, EC is probed via the radiations following it, here again the spectra are strongly resonant. (iii) As in the well-known tritium experiments, the information on the neutrino mass is conveyed through the events with nearly zero neutrino momentum. (iv) The intensity of such events is largest when Q_{EC} is close to the binding energy B_{ns} . (v) In this case the intensity is of the same order as in corresponding beta-decays, furthermore, the remaining parts of the spectrum will be suppressed compared to beta-decays; this facilitates experiments.

Attractive as this scheme sounds, it suffers from the practical drawback that there appears to be no candidates that fulfil the resonance condition, although some come close. The present paper is devoted to a case that has not been discussed previously, the long-lived isotope ^{81}Kr with decay scheme as shown in the inset of Fig. 1. The ground-state transition, being highly hindered of the type "first-forbidden unique", is responsible for the long half-life of $(2.1 \pm 0.2) \cdot 10^5$ years [3]. The transition of potential interest for neutrino mass experiments is an "inner" branch to the 276.0 keV $5/2^-$ level and has been detected by Schima [4], who in a preliminary communication reported an intensity of 3.7 ± 1.0 %. A new and accurate remeasurement of Q_{EC} by nuclear reaction spectroscopy [5] gave 280.9 ± 1.5 keV, so that the inner transition to $^{81}\text{Br}^*$ has a Q_{EC} value of 4.9 ± 1.5 keV, two standard deviations above the 2s resonance point of 1.78 keV. We report here experiments to redetermine the intensity of the inner branch and to measure its decay energy more accurately.

The ISOLDE Facility at CERN offers an exceptional possibility for producing strong and very pure samples of ^{81}Kr via the decay of 4.6 hour ^{81}Rb , which is available as a mass-separated secondary beam with an intensity of 10^{11} atoms per second. The beam was stopped in tin foils, which after collection contained 10^{15} to 10^{16} atoms of the activity of interest together with some cross contamination from the separator, mainly 10^{10} atoms of each of the activities ^{82}Sr , ^{83}Rb and ^{84}Rb with half-lives in the range of 25 to 86 days. These could be removed by careful heating of the foils to the melting point of tin so that only the krypton gas was released into a sealed vessel. (The 10.7 year ^{85}Kr is not produced in this scheme since ^{85}Rb is stable, and since krypton is not ionized in ISOLDE's surface-ionization ion sources.) We estimated the total decontamination factor to be at least 10^{-10} when measurements began 6 months after the collection of the sources.

In the first experiment the activity was transferred to a 2.8 cm^3 cavity with $20 \mu\text{m}$ Al-windows. This thickness will transmit 90 % of the Br K x-rays and all of the 276 keV gamma rays, the relative intensities of which were measured with a Ge detector, that was subsequently efficiency calibrated with ^{241}Am and ^{133}Ba sources. As a check, the absolute disintegration rates were also measured (here using a NaI

detector for the 276 keV line). The measured ratio of rates converts, after correcting for detector efficiencies, fluorescence yields etc., into a branching ratio of $(3.0 \pm 0.2) \cdot 10^{-3}$. This is appreciably lower than the previously reported value [4] of $3.7 \cdot 10^{-2}$.

Figure 1: Total absorption spectrum of L- and M-peaks following electron capture to the first excited state in ^{81}Br measured in a gas proportional counter. The spectrum, here corrected for background, was taken in coincidence with the 276 keV gamma ray measured in a NaI detector (total counting time 7.8 days). The inset shows the M peak on an expanded scale (only data from 3 days are included here). The asymmetric shape is due partly to the tail in the response function, partly to the electronic cut-off.

The second experiment aimed at a precise determination of the Q_{EC} value for the inner transition through a measurement of its M/L capture ratio. To this end, the Kr activity was introduced into a proportional counter together with a counting gas consisting of 90 % argon and 10 % methane. The atomic cascade following the electron capture was detected in the gas counter whilst the gamma ray from the beta transition to the first excited state was detected in a NaI detector placed next to it. A coincidence between the two detectors was employed to pick out the decays to the

first excited state and a gate was set on the 276 keV line in the NaI detector. The final spectrum after background subtraction is shown in Figure 1. There were essentially no randoms and a small background only in the gate in the NaI detector, for which a correction of approximately 12 % was obtained by recording coincidences with the gate condition set above and below the 276 keV peak.

The energy calibration of the gas counter was based on a ^{55}Fe source and a pulser and agreed with the known energies in the singles spectrum. The electronic coincidence efficiency was checked with a pulser and was constant over a range corresponding to energies in the gas detector from 6 keV down to 60 eV. (Due to electronic noise, the cut-off was set at 90 eV.) The response function of the gas detector was measured with a separate set-up. A Si(Li)-detector was used here to detect the escaping K_α and K_β x-rays in coincidence with the corresponding L and M deexcitations in the gas counter. Owing to edge effects in the gas detector the L peak has a low-energy tail which was included in the calculation of its intensity. The M peak is poorly resolved, see the inset in Figure 1, and the problem of tails does not arise there. We obtain an intensity ratio $M/L = 0.42 \pm 0.05$, with the uncertainty dominated by systematic errors.

Capture from the atomic N shell will not contribute to the measured M peak since the binding energy [6] of the 4s electron in bromine is around 27 eV only. Based on the atomic wavefunctions given by Bambynek et. al. [7] the M/L ratio corresponds to $Q_{EC} = 4.7 \pm 0.5$ keV, considerably more accurate than but in good agreement with the value 4.9 ± 1.5 keV obtained in the reaction experiments [5]. (We have assumed that the ratios of capture rates for first-forbidden, non-unique beta decays can be accounted for by the functions valid for allowed decays. This is normally the case, but not necessarily for a highly hindered decay such as the one that we are dealing with. We show below that the contribution of type first-forbidden unique must be small.)

From the Q_{EC} value one may calculate that the inner transition in ^{81}Kr is very strongly hindered with a $\log ft$ value of 9.3. In itself this is maybe understandable, since there is no first-forbidden strength available within the valence shell; any strength must come from transitions that connect to completely open or completely filled shells. It is, however, curious that the analogous transition in the nucleus with two more protons, ^{83}Sr , is 500 times faster with a $\log ft$ of 6.6 only. We have no explanation to suggest for this. One might be tempted to believe that the high $\log ft$ value could imply a sizeable unique-forbidden contribution to the inner transition of ^{81}Kr , but one can argue that this is unlikely to be the case: Assume a hypothetical unique component to have the same strength as that of the ground-state decay, and one calculates a contribution of approximately 0.1 %, arising mainly from capture in the $p_{3/2}$ atomic states. The reason for this is the stronger energy dependence of the f_1 -functions characterizing first-forbidden unique decays.

The ^{81}Kr branch studied in the present work is weak and far from resonance, and is clearly not an interesting candidate for neutrino-mass experiments. We give in Table 1 a summary of our results together with a selection of key data for other nu-

Table 1: Near-resonant EC beta decays.

Nucleus AZ					Atom $Z - 1$	
AZ	$T_{1/2}$ years	Branch %	Q_{EC}^a keV	Ref.	nl	B_{nl} keV
^{81}Kr	$2.1(2) \cdot 10^5$	$3.0(2) \cdot 10^{-3}$	4.7(5)	3, this work	2s	1.78
^{157}Tb	99(10)	$1.1(1) \cdot 10^{-3}$	8.0(5)	10, 11	2s	8.38
^{158}Tb	180(11)	3.8	35(3)	12, 13	1s	50.24
^{163}Ho	4570(50) 4569(27)	100	2.3(10)	14, 15	3s	2.05
			2.77(2) ^b	16		
			2.71(6) ^c	16		
			2.56(2) ^b	17		
			2.82(8) ^d	17		
			2.60(3) ^d	18		
^{193}Pt	50(9)	100	2.71(1) ^e	9	1s	76.11
			56.6(3) ^e	19, 20		

^a Q_{EC} refers to the transition of interest, thus for ^{81}Kr , ^{157}Tb and ^{158}Tb to the inner transition.

^b Recalculated from M/total ratio, from measured M-capture half-lives.

^c Recalculated, from measured M_1/M_2 ratio.

^d From measured N/M ratios.

^e From fit of the internal bremsstrahlung spectrum.

clides that have been considered for m_ν experiments based on resonant decays. The isotope ^{157}Tb might well be closest to resonance, but the inner branch is too weak and furthermore internally converted to 90 %. The best case still remains ^{163}Ho , although only in a total-absorption experiment as a theoretically predicted kink [8] near the end-point makes a bremsstrahlung experiment less attractive. The situation with electron capture is therefore rather dismal: all of the "obvious" candidates for precise neutrino mass measurements have been looked at in detail, and Nature has been unkind enough not to provide an isotope with the hoped-for characteristics. Until the technical challenges to the total-absorption technique have been solved one can therefore not expect major improvements upon the present [9] limit on the mass of the electron neutrino.¹

¹ The limit of 225 eV in this reference depends on Q_{EC} of ^{163}Ho which was assumed to be less than 2.64 keV. In view of the data of Table 1 this seems too optimistic, a more realistic limit being around 300 eV.

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