ORBITAL ELECTRON CAPTURE AND β^+ DECAY OF H-LIKE ^{140}Pr IONS *

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For the first time the electron capture and β^+ decay rates of H-like ^{140}Pr ions have been measured at the FRS-ESR facility by using the Schottky noise technique. The H-like $^{140}\mathrm{Pr}^{58+}$ decay rate was found to be larger by a factor of 1.5 than in the case of neutral atom. This non-intuitive result can be explained by taking into account hyperfine splitting of nuclear levels in the decaying nuclei and the conservation law of the total angular momentum of the system.

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1. Introduction

Ever since the discovery of radioactivity by Becquerel in 1896 [1] a large number of attempts has been made in order to observe the modification of nuclear lifetime by applying high pressure, strong electromagnetic fields or huge acceleration [2].

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It has been apprehended relatively soon that the number of electrons bound in the atom could modify considerably, or even dramatically [3], the lifetime of the corresponding nucleus.

With the development of heavy-ion storage rings we have the new opportunity to study half-lives of highly ionised radioactive nuclei. Highly charged ions can be found inside stellar environments, thus precise investigations of the β decay rates of these ions might help us to understand better many aspects of the stellar nucleosynthesis.

2. Experiment

The experiment was performed at the SIS synchrotron of GSI Darmstadt, which delivered a 508 A GeV ^{152}Sm beam with an intensity of the order of 10^9 ions/spill. The ions of interest, ^{140}Pr, were produced in the projectile fragmentation reaction on a 1 g/cm^2 thick beryllium target placed at the entrance to the projectile FRagment Separator (FRS) [4]. The reaction products were separated by the FRS operated in the achromatic with an energy degrader mode. After passing the magnetic sections of the separator the selected ions were injected into the ESR storage ring [5], where circulating with a revolution frequency of the order of 2 MHz they could be kept for extended periods of time.

The ESR is equipped with a set of Schottky noise probes which collect the mirror charge of each passing ion, thus providing the information about its revolution frequency. In case of two different ions their revolution frequencies f_i and f_j can be related to their relative difference of the (m/q)-ratio by the following expression:

$$\frac{f_j - f_i}{f_i} = -\frac{1}{\gamma_t^2}\frac{(m/q)_j - (m/q)_i}{(m/q)_i} + \frac{v_j - v_i}{v_i}\left(1 - \frac{\gamma_i^2}{\gamma_t^2}\right) , \tag{1}$$

where v_i, v_j are the ions velocities, γ_i is the Lorentz factor, $\gamma_t = 1/\sqrt{\alpha_p}$ and α_p is the momentum compaction factor characterising the relative variation of the orbital length per relative variation of the magnetic rigidity [6]. Both, stochastic [7] and electron [8] cooling were applied in an attempt to decrease the velocity spread $\Delta v = v_j - v_i$ of the circulating ions, thus making the second term in Eq. (1) negligible. Then a one-to-one correspondence between the relative revolution frequencies and the relative (m/q)-ratio could have been established, yielding a high mass resolving power and providing an unambiguous isotopic and charge state identification. This approach is the basis of the Schottky Mass Spectrometry method [6, 10].

The ^{140}Pr decays by electron capture and β^+ transition with a half-life of 203.4(6)s and a $Q_{\rm EC}$ value of 3388(7) keV [9]. The main decay branch with 99.4% relative intensity is an allowed transition between 1^+ and 0^+ ground states. The half-life of this β-decaying level is obviously appropriate for the Schottky Mass Spectroscopy which requires several seconds of cooling time. In Fig. 1 typical Schottky frequency spectra registered 50s and 1500s after the injection of the fragments into the ESR, respectively, are shown. The area of the frequency peaks is proportional to the number of stored ions [10].

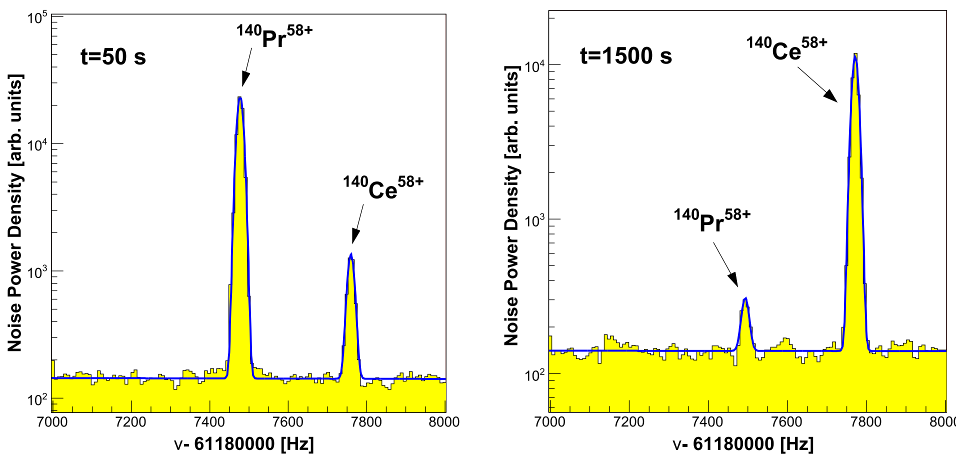

Fig. 1. Schottky noise density spectra registered 50 s and 1500 s after the injection of the fragments into the ESR, respectively. The peak intensity corresponds to the number of stored $^{140}\mathrm{Pr}^{58+}$ and $^{140}\mathrm{Ce}^{58+}$ ions. The presented spectra are the result of averaging of 100 data blocks.

3. Data analysis and results

Analysing the frequency peaks present in the subsequently accumulated Schottky spectra, a time distribution of the number of H-like Pr and Ce ions stored in the ESR was constructed (see Fig. 2). The time evolution of the number of $^{140}\mathrm{Pr}^{58+}$ ions can be described by the following expression

$$N_{\mathrm{Pr}}(t) = N_{\mathrm{Pr}}(0)e^{-\lambda t}\,, \tag{2}$$

where $N_{\mathrm{Pr}}(0)$ is the number of stored Pr ions at the beginning of the measurement and $\lambda = \lambda_{\beta+} + \lambda_{\mathrm{EC}} + \lambda_{\mathrm{loss}}$ is the decay constant consisting of three components responsible for β^+-decay, electron capture decay and non-radioactive losses in the ring, respectively. In the case of the daughter activity the number of stored $^{140}\mathrm{Ce}^{58+}$ ions is given by

$$N_{\mathrm{Ce}}(t) = N_{\mathrm{Pr}}(0)\frac{\lambda_{\mathrm{EC}}}{\lambda - \lambda_{\mathrm{loss}}}(e^{-\lambda_{\mathrm{loss}}t} - e^{-\lambda t}) + N_{\mathrm{Ce}}(0)e^{-\lambda_{\mathrm{loss}}t}, \tag{3}$$

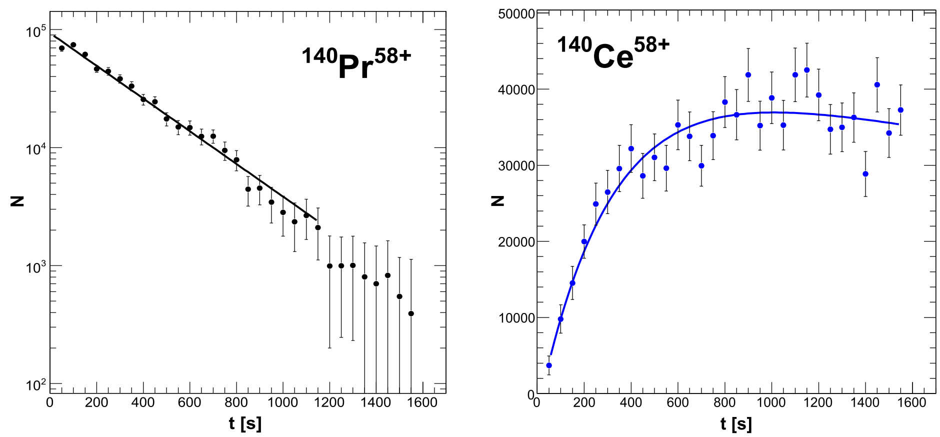

Fig. 2. Time distribution in laboratory frame of the number of Pr (left panel) and Ce (right panel) ions stored in the ESR. The continuous line shows the fitted theoretical dependence given by Eqs. (2) and (3), respectively. Data taken during one single measurement.

where $N_{\mathrm{Ce}}(0)$ is the number of Ce ions at the beginning of the measurement. Note that the events present in the Ce frequency peak originate only from the electron capture transition. The β^+-decay products have a larger (m/q)-ratio, therefore events corresponding to that decay branch are being placed in a different region of the revolution frequency.

In the case of H-like ^{140}Pr atom the hyperfine interaction between the electron and the nucleus splits the $I_i = 1$ nuclear state into two levels with a total angular momentum of $F = 1/2$ and $F = 3/2$. In the final state the total angular momentum of the system can only have one value $F = 1/2$, resulting from the coupling of the $I_f = 0$ angular momentum of the ^{140}Ce nucleus and the $s = 1/2$ spin of the emitted neutrino. Based on the systematics of neighbouring odd-A nuclei the value of the magnetic moment of ^{140}Pr was deduced to be $\mu = +2.5\mu_N$, hence, the lower hyperfine state is assigned to the $F = 1/2$ level. Therefore, only transitions from the $F = 1/2$ hyperfine level can participate in the allowed decay to the final state in ^{140}Ce. The simplified decay scheme of H-like ^{140}Pr is shown in Fig. 3.

Several measurements of the decay constant of $^{140}\mathrm{Pr}^{58+}$ have been performed showing overall consistent results. The average decay rates for electron capture and β^+ processes are given in Table I. In the case of the β^+ decay branch the measured decay rate value for the H-like ^{140}Pr is comparable within the limits of uncertainty to the value calculated for a neutral atom. Though this is an expected behaviour since the modification of the Fermi function related to the electron screening as well as the difference in the Q_{EC} value between H-like and neutral atoms changes the decay rate by around 2% — a value being placed far below our measurement precision.

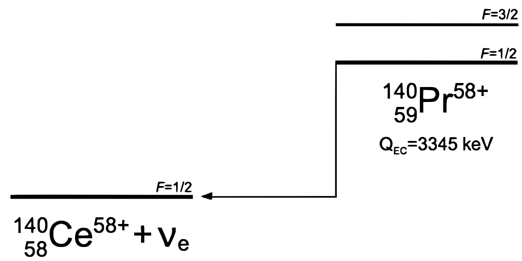

Fig. 3. The decay scheme of the H-like ^{140}Pr. The $F = 1/2$ and $3/2$ levels in ^{140}Pr^{58+} result from the coupling of nuclear and electron spins, the $F = 1/2$ total angular momentum value of the final state is the sum of the ^{140}Ce nucleus angular momentum and the spin of the neutrino emitted in the electron capture process.

TABLE I

The measured decay constants for β^+ and electron capture transitions in H-like ^{140}Pr. The decay constants for neutral ^{140}Pr are given for comparison. All values refer to the laboratory frame.

	λ [s^{-1}]	λ_{EC} [s^{-1}]	λ_{β^+} [s^{-1}]
^{140}Pr^0	$3.388(10)\times10^{-3}$	$1.647(11)\times10^{-3}$	$1.741(11)\times10^{-3}$
^{140}Pr^{58+}	$3.7(2)\times10^{-3}$	$2.21(8)\times10^{-3}$	$1.5(4)\times10^{-3}$

It might be interesting to notice that the λ value is larger for H-like Pr atoms than for neutral ones. Moreover, the difference becomes even larger for the λ_{EC} decay constant. This remains in opposition to the naive approximation suggesting that the orbital capture probability is proportional to the number of orbital K electrons. In particular, the decay rate for H-like ions λ_{H} should be related to the decay rate of a He-like ions by the following expression [11]

$$\lambda_{\mathrm{H}} = \frac{1}{2}\lambda_{\mathrm{He}}\,. \tag{4}$$

However, the experimental result $\lambda_{\mathrm{H}} = 1.59(6)\lambda_{\mathrm{He}}$ exceeds the simple prediction by over three times. Here the λ_{He} value has been deduced from the decay constant of the neutral atom and the K-shell to total electron capture probability ratio $b_{\mathrm{K/EC}} = 0.85$. A detailed derivation shows [12] that for the $\Delta I = I_f - I_i = -1$ electron capture transitions

$$\lambda_{\mathrm{H}} = \frac{3}{2}\lambda_{\mathrm{He}}\,, \tag{5}$$

which is in a very good agreement with the measured value given in this work. This result has been confirmed in a recent experiment performed at GSI where the decay rates of both H-like and He-like ^{140}Pr have been measured yielding $\lambda_{\mathrm{H}} = 1.49(8)\lambda_{\mathrm{He}}$ [13].

4. Summary

In the reported experiment the electron capture and β^+ processes have been investigated in H-like ions for the first time. The decay rates measurements show that reducing the number of the shell electrons in the decaying atom increases the probability of the electron capture transition. The obtained result has been explained by taking into account the conservation of the total angular momentum of the nucleus-lepton system and including the hyperfine interaction in the theory of the electron capture decay. As a future aim, the measurement of the H-like ^{64}Cu lifetime is scheduled [14]. The negative value of its magnetic momentum assigns the lower hyperfine state to the $F = 3/2$ total angular momentum. Therefore the electron capture transition to the ^{64}Ni ground state ($I_f = 0$, $F = 1/2$) should be strongly hindered.

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