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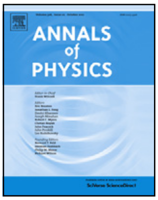

The role of spin–rotation coupling in the non-exponential decay of hydrogen-like heavy ions

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ABSTRACT

Recent experiments carried out at the storage ring of GSI in Darmstadt reveal an unexpected oscillation in the orbital electron capture and subsequent decay of hydrogen-like $^{140}\text{Pr}^{58+}$, $^{142}\text{Pm}^{60+}$ and $^{122}\text{I}^{52+}$. The modulations have periods of 7.069(8) s, 7.10(22) s and 6.1 s respectively in the laboratory frame and are superimposed on the expected exponential decays.

In this paper we propose a semiclassical model in which the observed modulations arise from the coupling of rotation to the spins of electron and nucleus. We show that the modulations are connected to quantum beats and to the effect of the Thomas precession on the spins of bound electron and nucleus, the magnetic moment precessions of electron and nucleus and their cyclotron frequencies. We also show that the spin–spin coupling of electron and nucleus, though dominant relative to the magnetic moment coupling of electron and nucleus with the storage ring magnetic field, does not contribute to the modulation because these terms average out during the time of flight of the ions, or cancel out. The model also predicts that the anomaly cannot be observed if the motion of the ions is rectilinear, or if the ions are stopped in a target (decay of neutral atoms in solid environments). It also supports the notion that no modulation occurs for the β^+-decay branch.

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1. Introduction

In recent experiments carried out at the storage ring of the GSI in Darmstadt [1–3], the lifetime of several highly charged ions has been measured via electron capture (EC). In these experiments Sm-projectiles (primary beam) hit a Be-target producing ions (most of them completely stripped) from several isotopes. Ions of a certain ratio M/Q are separated in flight by means of a magnetic field and are then injected (two ions in the average) in the Experimental Storage Ring (ESR). The velocity spread $\Delta v/v$ of the ions is reduced to only about 10^{-7} by applying stochastic cooling in the first few seconds and also by applying a permanent electron cooling. The final result is that the revolution frequency is only a function of M/Q and can be used to identify the respective ion. The frequency is monitored by using Schottky pickups, whose strength is proportional to the number of ions of the same frequency. By time-resolved monitoring of these signals for a certain band of frequencies, the disappearance times of the mother ions and the appearance times of the daughter nuclei can be determined very accurately [1,2].

The results of these experiments show that the decay law of hydrogen-like (H-like) ions is not purely exponential, but contains, surprisingly, an additional superimposed periodic modulation. The H-like ions initially used in the experiment are the Praseodymium $^{140}\mathrm{Pr}^{58+}$ and the Promethium $^{142}\mathrm{Pm}^{60+}$. More recently the experiment has been performed with Iodine $^{122}\mathrm{I}^{52+}$, confirming the modulation in the decay law observed for the Pr and Pm ions [4,5]. The three nuclei decay to stable daughters either via β^+ decay or by the two body EC decay. The systems decay mainly by a single allowed Gamow–Teller transition ($1^+ \to 0^+$)

$$\begin{aligned}
&{}^{140}\,\mathrm{Pr}^{58+} \to {}^{140}\mathrm{Ce}^{58+} + \nu_e,\\
&{}^{142}\mathrm{Pm}^{60+} \to {}^{142}\mathrm{Nd}^{60+} + \nu_e,\\
&{}^{122}\mathrm{I}^{52+} \to {}^{122}\mathrm{Te}^{52+} + \nu_e.
\end{aligned}$$

To account for the modulation, the data have been fitted with the function [1,2]

$$\frac{dN_{EC}}{dt} = N(0)\, e^{-\Gamma t}[1 + a\, \cos(\omega t + \varpi)], \tag{1}$$

where $N(0)$ is the number of parent ions at the time $t = 0$. The decay constant is $\Gamma = \lambda_{EC} + \lambda_{\beta^+} + \lambda_{\,\mathrm{loss}}$, where λ_{EC} is the EC decay constant, λ_{β^+} that of the β^+-decay and $\lambda_{\,\mathrm{loss}}$ the loss constant. The values of the amplitude of the oscillations a are [4]

$$\begin{aligned}
&a({}^{140}\,\mathrm{Pr}^{58+}) = 0.18(3), \qquad a({}^{142}\mathrm{Pm}^{60+}) = 0.23(4),\\
&a({}^{122}\mathrm{I}^{52+}) = 0.22(2),
\end{aligned} \tag{2}$$

while the angular frequency ω is related to the period T by $\omega = 2\pi/T$. The GSI experiments give

$$\begin{aligned}
&T({}^{140}\,\mathrm{Pr}^{58+}) = 7.069(8)\ \mathrm{s}, \qquad T({}^{142}\mathrm{Pm}^{60+}) = 7.10(2)\ \mathrm{s},\\
&T({}^{122}\mathrm{I}^{52+}) = 6.1\ \mathrm{s}.
\end{aligned} \tag{3}$$

Finally the phase ϖ reflects the different time needed to cool the recoiling daughter ions [2].

In addition, the GSI experiments provide other important results (see the reviews [4–6]).

- No modulation of the decay probability is observed for the β^+ branch.
- A possible oscillatory transition with a period T between the active $F = 1/2$ hyperfine ground state to the sterile $F = 3/2$ excited state is excluded.
- Indications that T scales with the mass number A of the decaying system.

Another important point must be stressed with respect to conservation of total angular momentum $\mathbf{F} = \mathbf{I} + \mathbf{s}$. The $^{140}\mathrm{Pr}^{58+}$ and $^{142}\mathrm{Pm}^{60+}$ ions have nuclear spin $I = 1$ while the bound K electron has spin $s = 1/2$. The initial states can have two values of the hyperfine states, $F = I - s = 1/2$ for antiparallel spins, and $F = I + s = 3/2$ for parallel spins. In the final state, after the decay, the total angular momentum can assume only the value $F = 1/2$, because $I_{^{140}Ce} = 0$ and $s_{\nu_e} = 1/2$, while the decay from $F = 3/2$ is forbidden because the emitted neutrino would carry away an orbital angular momentum