Simultaneous Measurement of β^- Decay to Bound and Continuum Electron States

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We report the first measurement of a ratio $\lambda_{\beta_b}/\lambda_{\beta_c}$ of bound-state (λ_{β_b}) and continuum-state (λ_{β_c}) β^--decay rates for the case of bare $^{207}Tl^{81+}$ ions. These ions were produced at the GSI fragment separator FRS by projectile fragmentation of a ^{208}Pb beam. After in-flight separation with the $B\rho$-ΔE-$B\rho$ method, they were injected into the experimental storage-ring ESR at an energy of 400.5A MeV, stored, and electron cooled. The number of both the $^{207}Tl^{81+}$ ions and their bound-state β^--decay daughters, hydrogenlike $^{207}Pb^{81+}$ ions, were measured as a function of storage time by recording their Schottky-noise intensities. The experimental result, $\lambda_{\beta_b}/\lambda_{\beta_c} = 0.188(18)$, is in very good agreement with the value of 0.171(1) obtained from theory employing spectra of allowed transitions.

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Beta-decay strengths influence nuclear transmutations, the pathways of stellar nucleosynthesis in stars and the resulting abundance of atomic nuclei. These strengths depend not solely on the nuclear transition matrix elements and Q values (mass differences), but also on the number of bound electrons, i.e., on the ionic charge state q. For β^+ decays the ratio of orbital electron capture (EC) and continuum β^+ decay, $R(\beta^+) = \lambda_{EC}/\lambda_{\beta^+}$, has been explored extensively by theory [1] and a multitude of measurements [2]. For the time-mirrored β^- decay, however, the corresponding ratios $R(\beta^-) = \lambda_{\beta_b}/\lambda_{\beta_c}$, for electron emission to bound (β_b) and continuum states (β_c), have not yet been addressed by experiments.

The $R(\beta^+, \beta^-)$ renders—besides small corrections—the ratio of all bound-electron states of the mother (daughter) atoms and of the densities for continuum positron (electron) states at the origin, as comprised in the Fermi function. Whereas $R(\beta^+)$ decreases with decreasing number of bound electrons, $R(\beta^-)$ exhibits just the opposite behavior: if the number of bound electrons is reduced, more and more empty states—Pauli-blocked before—become available for bound-state β^- decay and hence $R(\beta^-)$ grows. Because of the newly available phase space for the released electron also the *total* β^--decay probability increases. For a given ionic charge state q the ratio $R(\beta^-)$ is maximized for small Q values.

In particular, the pathways of hot stellar nucleosynthesis might be altered meaningfully by a high ionic charge state q, because it enables new branchings due to enhanced bound-state β^- decays. Vice versa: from measured nuclear abundances in the vicinity of those branching points the mean ionic charge state $\langle q \rangle$ and, thus, the stellar temperature may be constrained, e.g., for the s process [3], provided $R(\beta^-)$ is known as a function of q.

For about a decade ion storage-cooler rings have offered the opportunity to explore β^- decay of *highly charged* ions. For the first measurement of a β_b/β_c branching ratio, as reported here, we have chosen a technique by which the number of both the mother ions and their β_b daughters can be recorded simultaneously as a function of time. Best suited for this purpose is time-resolved Schottky mass spectrometry on stored and cooled ions [4]. To maximize the relative yield of β_b decays, the Q value of β^- decay should be as small as possible. On the other hand, the Q value has to be sufficiently large in order to avoid too long half-lives and to resolve the signals of mother and β_b daughter in the Schottky frequency spectrum. As a compromise, these somewhat conflicting constraints led to the choice of bare $^{207}Tl^{81+}$ as mother ions with a neutral-atom β^- half-life of 4.77 min and a neutral-atom Q value of 1.418 MeV [5]. The $1/2^+$ g.s. of neutral $^{207}Tl^0$ decays by a nonunique first-forbidden transition with 100% to the $1/2^-$g.s. of ^{207}Pb.

Figure 1 shows the experimental setup. Highly charged ^{208}Pb ions were accelerated in the heavy-ion synchrotron SIS to a kinetic energy of 838A MeV and transported to the

4 g/cm^2 thick beryllium production target at the entrance of the fragment separator FRS [6]. In fragmentation reactions in the target ^{207}Tl is produced with a cross section of about 30 mb [7]. The cocktail of the fragments was analyzed by the FRS as shown in Fig. 1, using a two-stage magnetic separation with a wedge shaped degrader in between ($B\rho$-ΔE-$B\rho$ method [6]), which introduces an energy loss, roughly proportional to the square of the atomic number of the ion species. This way isotopic separation of ^{207}Tl^{81+} at the exit slit of the FRS is achieved. Special care was taken to separate bare ^{207}Tl^{81+} ions from nearby H-like ^{207}Pb^{81+} ions (the β_b daughters of ^{207}Tl^{81+}) by using a sufficiently thick degrader, its thickness corresponding to 35% of the range. Thereby the fraction of ^{207}Pb^{81+} ions injected at an energy of 400.5A MeV into the ESR [8] was reduced to only a few percent of corresponding bare ^{207}Tl^{81+} ions.

After injection of an almost pure bunch of bare ^{207}Tl^{81+} ions into the ESR, electron cooling [9] was applied with a current of 200 mA, which generates brilliant beams of highest phase space density, i.e., of small transverse emittance and velocity spread ($\delta v/v = 10^{-5} \ldots 10^{-7}$). It enabled, moreover, $1/e$-storage times of about 40 minutes for these heavy highly charged ions at a residual gas pressure of about 10^{-11} mbar. However, for "hot" fragments with a large initial velocity spread, as produced by fragmentation,

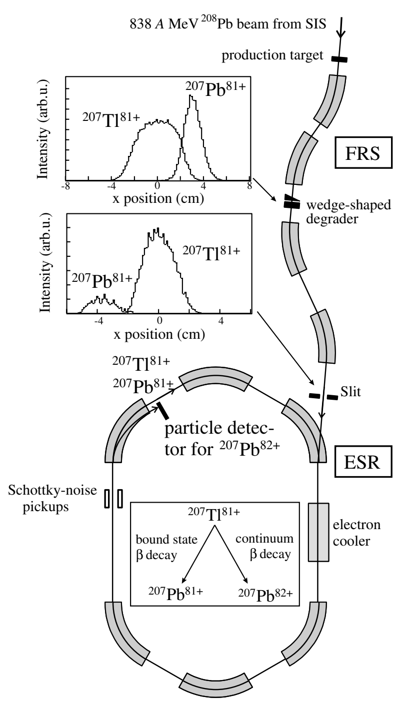

FIG. 1. Schematic view of the experimental setup. The spatial separation of the mother nuclei ^{207}Tl^{81+} from the H-like ^{207}Pb^{81+} daughter ions (the number of the latter must be minimized at injection) is illustrated by the insets showing calculated position distributions at the degrader and in front of the exit slit of the FRS. For details, see text.

electron cooling requires a rather long time in the order of one to two minutes. The reason is that the cooling time increases as Δv^3, where Δv denotes the difference of the ion velocity and the velocity of the cooler electrons. After complete electron cooling, all stored ions circulate at almost the same velocity due to the repeated interaction with the cold cooler electrons, which they traverse with a circulation frequency of about 2 MHz. The coasting ions induce a Schottky-noise signal when passing the pair of capacitive pickup plates mounted inside the storage-ring aperture. The Fourier-transformed signals appear at distinct frequencies ("Schottky lines") that correspond to the mass-to-charge ratio m/q of each stored ion species.

The data were recorded and processed using a Sony/Tektronix spectrum analyzer "Model 3066." Starting at the time of injection of an ion bunch, the signals of the Schottky-pickups were recorded for subsequent time intervals of 320 ms (or 640 ms) duration, online analyzed by a fast-fourier-transform, and the resulting frequency spectra were stored. From these signals, taken at the 30th harmonic of the revolution frequency $f = 1.978$ MHz of the ions, the frequency of an internal local oscillator operating at 59 340 500 Hz was subtracted. The resulting spectra were stored covering a 1 kHz band and comprising 640 channels, thus yielding a resolution of 1.56 Hz (3.12 Hz) per channel. In order to increase the signal-to-noise ratio, the data have been averaged over 100 single spectra, corresponding to 32 s (64 s), after a minor correction for slow frequency shifts caused by small drifts of the power supplies of the ESR. In total, 4000 single spectra of 320 ms (640 ms) duration were accumulated, corresponding to an overall measuring time of 1280 s (2560 s).

Figure 2 presents the first *direct* observation of β_b decay. The spectra, taken at various times t after injection, exhibit well-resolved lines of the ^{207}Tl^{81+} mother ions and their H-like ^{207}Pb^{81+} β_b daughters. In the two-body β_b decay, the atomic charge q does *not* change, since the released electron remains bound in the daughter atom. Thus the couple of mother and β_b daughter ions leaves a characteristic fingerprint in the Schottky frequency spectrum: it appears as close-lying lines, separated by only 82 (1) Hz at the 30th harmonic of about 59 MHz. This frequency spacing corresponds directly to the Q_{β_b} (K) value for a β_b transition to the K shell of ^{207}Pb^{81+}, since all transitions to higher-lying states relax very quickly to the bound-electron ground state. It should be stressed that in previous experiments addressing β_b decay [10,11], the β_b Schottky lines could not be resolved, due to very small Q values. Furthermore, the remarkable mass resolution $\delta m_{\mathrm{FWHM}}/m \simeq 1 \times 10^{-6}$ became possible because the number of injected ^{207}Tl^{81+} ions was kept below the value of about 2000: at about this number a phase transition to an ordered linear ion chain has been observed [12], leading to an almost negligible relative momentum spread ($\sim 10^{-7}$) of the revolving "frozen" ions. From the areas of the Schottky lines

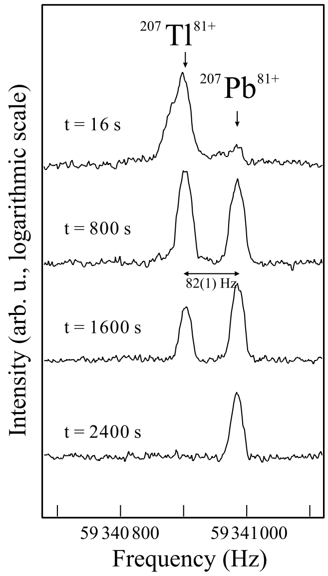

FIG. 2. Schottky frequency spectra of $^{207}Tl^{81+}$ ions and their H-like β_b daughters $^{207}Pb^{81+}$, at various times after injection of $^{207}Tl^{81+}$ ions into the ESR. From the first spectrum after injection ($t = 16$ s) it is clearly seen that the cooling process is not yet completed (see text). After complete cooling, the revolution frequencies of both ion species appear well separated by 82(1) Hz at the 30th harmonic. The particular feature here is the *simultaneous* and thus *direct*, time-resolved observation of the number of both mother and daughter ions.

one obtains at each time interval the number N of the corresponding ion species, as these intensities are proportional to q^2N. As can be seen from Fig. 3, a bunch containing about 1900 $^{207}Tl^{81+}$ ions was injected, containing a few (about 20) $^{207}Pb^{81+}$ ions. The time-resolved Schottky spectroscopy was applied solely to the small frequency range comprising $^{207}Tl^{81+}$ mother ions and the near-lying $^{207}Pb^{81+}$ bound-state β^--decay daughter ions.

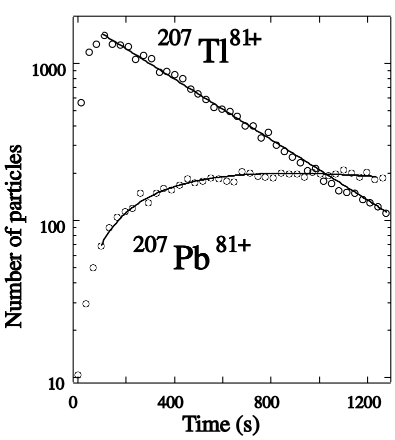

FIG. 3. Number of stored bare $^{207}Tl^{81+}$ ions and their β_b daughters $^{207}Pb^{81+}$ as a function of the storage time in the ESR. The statistical errors for most data points are smaller than the size of the symbols.

The time evolution of the number $N_{\mathrm{Tl}}(t)$ of the bare $^{207}Tl^{81+}$ mother ions and of the number $N_{\mathrm{Pb}}(t)$ of the H-like $^{207}Pb^{81+}$ β_b daughter ions is given by

$$N_{\mathrm{Tl}}(t) = N_{\mathrm{Tl}}(0)\exp(-\lambda t), \tag{1}$$

$$N_{\mathrm{Pb}}(t) = N_{\mathrm{Tl}}(0)\frac{\lambda_{\beta_b}}{\lambda_{\beta_c} + \lambda_{\beta_b}}[\exp(-\lambda_{\mathrm{loss}}t) - \exp(-\lambda t)] + N_{\mathrm{Pb}}(0)\exp(-\lambda_{\mathrm{loss}}t) \tag{2}$$

where $N_{\mathrm{Tl}}(0)$, $N_{\mathrm{Pb}}(0)$ are the corresponding ion numbers present at the time of injection ($t = 0$). The total decay constant $\lambda = \lambda_{\beta_c} + \lambda_{\beta_b} + \lambda_{\mathrm{loss}}$ is the sum of the decay probabilities to continuum (λ_{β_c}) and bound states (λ_{β_b}) and the loss rate λ_{loss}, which denotes an additional reduction for both, bare Tl and H-like Pb ions, due to unavoidable beam losses in the machine and (atomic) charge changing processes in the electron cooler or the residual gas. In previous experiments [10,11] it has been shown that for neighboring bare and H-like heavy ions the corresponding λ_{loss} constants are nearly equal (compared with bare ions, the slightly smaller electron capture rate in the cooler for H-like ions is, accidentally, nearly compensated by an additional ionization rate in the residual gas for a pressure of about 10^{-11} mbar and for a gas containing mainly hydrogen).

Figure 3 shows as a function of time the number of $^{207}Tl^{81+}$ mother ions and their β_b daughters, H-like $^{207}Pb^{81+}$ ions, taken over 1280 s. In long-time runs the number of Tl ions could be finally reduced to one single ion. Therewith the Schottky-noise intensity corresponding to 1, 2, 3, ..., n Tl ion(s) was determined. Since the charge state $q = 81$ is identical for both ion species, the same calibration could be applied for the Pb ions.

The data analysis proceeded via the following steps: First, long-time runs exceeding more than 40 min. were exploited to determine λ_{loss} by a separate fit to the Pb data from the time regime after the complete decay of the Tl ions. Then, from a fit of all available Tl data according to Eq. (1), the initial number of Tl ions, $N_{\mathrm{Tl}}(0)$, the total decay constant λ in the laboratory system and, hence, $\lambda_{\beta_c} + \lambda_{\beta_b} = \lambda - \lambda_{\mathrm{loss}}$ were determined. Finally, the remaining parameters λ_{β_b} and $N_{\mathrm{Pb}}(0)$ were obtained from a fit to the Pb data according to Eq. (2). The first three points at 16 s, 48 s, and 80 s show significant deviations from the exponential decay curve, caused by the long time needed to cool the hot Tl fragments employing electron cooling. Therefore these points were excluded from the fits.

The results for the decay constants in the laboratory system are: $\lambda = 22.8(4) \times 10^{-4}\ \mathrm{s}^{-1}$, $\lambda_{\mathrm{loss}} = 3.8(7) \times 10^{-4}\ \mathrm{s}^{-1}$, $\lambda_{\beta_b} = 3.0(2) \times 10^{-4}\ \mathrm{s}^{-1}$, and, therewith, $\lambda_{\beta_c} = \lambda - \lambda_{\mathrm{loss}} - \lambda_{\beta_b} = 16.0(8) \times 10^{-4}\ \mathrm{s}^{-1}$. Our detection technique does not allow us to resolve transitions to individual atomic shells of the bound-electron states. Therefore, the above quoted λ_{β_b} value comprises the sum of all transition probabilities to bound states; we calculate that about 80% of the β_b transitions pass directly into the $1s_{1/2}$ state of ^{207}Pb. After transformation into the rest frame (r.f.) of the ions according to $\lambda(\text{r.f.}) = \gamma \times \lambda$, we obtain with a Lorentz factor $\gamma = 1.430(1)$ (determined from the voltage of the electron cooler) the following decay probabilities:

$$\begin{aligned} \lambda(\text{r.f., exp}) &= 32.6(6) \times 10^{-4}\ \text{s}^{-1}, \\ \lambda_{\beta b}(\text{r.f., exp}) &= 4.29(29) \times 10^{-4}\ \text{s}^{-1}, \\ \lambda_{\beta c}(\text{r.f., exp}) &= 22.9(12) \times 10^{-4}\ \text{s}^{-1}, \\ [\lambda_{\beta_b}/\lambda_{\beta_c}](\text{r.f., exp}) &= 0.188(18). \end{aligned} \tag{3}$$

An independent value of the total decay probability λ was provided by the particle detector which stopped and recorded the β_c daughters, bare $^{207}\text{Pb}^{82+}$ ions, at an appropriate position in the inner part of the aperture (see Fig. 1). The result, $\lambda(\text{r.f.}) = 39(7) \times 10^{-4}\ \text{s}^{-1}$, is in reasonable agreement with the value quoted in Eq. (3).

The partial and total β^--decay rates in the rest frame have to be compared with the value of neutral $^{207}\text{Tl}^0$, $\lambda(^{207}\text{Tl}^0) = 24.2 \times 10^{-4}\ \text{s}^{-1}$ [5], which is almost solely due to *continuum* β^- decay. The corresponding β_c-decay rate of bare $^{207}\text{Tl}^{81+}$ of $22.9 \times 10^{-4}\ \text{s}^{-1}$ is 5% smaller, whereas the total β^--decay rate of bare $^{207}\text{Tl}^{81+}$($27.2 \times 10^{-4}\ \text{s}^{-1}$) is 12% larger, due to the "new" β_b branch.

We calculate, by using "allowed spectra" of the continuum electrons and antineutrinos for the Fermi function in the continuum β^- decay, and relativistic hydrogenlike wave functions of the bound states (up to and including $6s_{1/2}$) for bound-state β^- decay to H-like $^{207}\text{Pb}^{81+}$ (see also [13]):

$$\begin{aligned} \lambda_{\beta_b}(\text{theo}) &= 4.06(2) \times 10^{-4}\ \text{s}^{-1}, \\ \lambda_{\beta_c}(\text{theo}) &= 23.7(2) \times 10^{-4}\ \text{s}^{-1}, \\ [\lambda_{\beta_b}/\lambda_{\beta_c}](\text{theo}) &= 0.171(1) \end{aligned} \tag{4}$$

in excellent agreement with the experimental values quoted in Eq. (3). It must be noted here, however, that the transition of our current interest is nonunique first-forbidden transitions. In principle, therefore, the above statement based on the "normal approximation" [14], i.e., the assumption of the allowed spectra, is not always valid. In some cases, non-negligible energy dependences that are different for different matrix elements may appear. In the present case of ^{207}Tl, the deviation from the allowed spectra seems to be small, however (some percent at maximum [15,16]), thus justifying the approximation made.

It should be noted that the absence of the atomic electrons leads to a smaller Q value for the continuum β decay (1401 keV instead of 1418 keV in the neutral atom [5]) and to the absence of screening of the nuclear charge. Both effects lead to a reduction of the continuum decay rate of the neutral atom [13] $\lambda_{\beta_c} = 24.2 \times 10^{-4}\ \text{s}^{-1}$ to the value given in Eq. (4). In addition to this "trivial" effect, the empty atomic shells of the bare nucleus provide the empty phase space for the released electron, which leads to the new decay channel of bound-state β decay and thus to a 15% increased *total* decay rate of $\lambda_\beta(\text{theo}) = 27.8(2) \times 10^{-4}\ \text{s}^{-1}$.

In conclusion, we have measured a bound-to-continuum ratio in β^- decay, the so far missing counterpart to the EC/β^+ ratio of β^+ decay. For the first time we have *directly* observed the bound-state β^- decay. Our results confirm within an uncertainty of a few percent calculations based on the assumption of the allowed spectra for the investigated nonunique first-forbidden β^- transition of bare $^{207}\text{Tl}^{81+}$.

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[1] H. Behrens and J. Jänecke in *Numerical Tables for Beta-Decay and Electron Capture* Landolt-Börnstein New Series (Springer-Verlag, Berlin, 1969), Vol. 4.
[2] W. Bambynek *et al.*, Rev. Mod. Phys. **49**, 77 (1977).
[3] F. Kaeppeler *et al.*, Annu. Rev. Nucl. Part. Sci. **48**, 175 (1998).
[4] B. Franzke, Phys. Scr. **T59**, 176 (1995), O. Klepper, Nucl. Phys. **A626**, 199c (1997), Yu. A. Litvinov *et al.*, Phys. Lett. B **573**, 80 (2003), and Yu. A. Litvinov *et al.*, Nucl. Phys. **A734**, 473 (2004).
[5] M. J. Martin, Nucl. Data Sheets **70**, 315 (1993).
[6] H. Geissel *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **204**, 71 (2003).
[7] K. Sümmerer *et al.*, Phys. Rev. C **61**, 034607 (2000).
[8] B. Franzke, Nucl. Instrum. Methods Phys. Res., Sect. B **24–25**, 18 (1987).
[9] M. Steck *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **532**, 357 (2004).
[10] M. Jung *et al.*, Phys. Rev. Lett. **69**, 2164 (1992).
[11] F. Bosch *et al.*, Phys. Rev. Lett. **77**, 5190 (1996).
[12] M. Steck *et al.*, Phys. Rev. Lett. **77**, 3803 (1996), and R. W. Hasse, Phys. Rev. Lett. **90**, 204801 (2003).
[13] K. Takahashi *et al.*, At. Data Nucl. Data Tables **36**, 375 (1987) and K. Takahashi *et al.*, Nucl. Phys. **A404**, 578 (1983).
[14] E. J. Konopinski and M. E. Rose in *Alpha-, Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1966), p. 1327.
[15] J. M. Trischuk *et al.*, Nucl. Phys. **A90**, 33 (1967).
[16] J. Eichler, Z. Phys. **171**, 463 (1963).