Half-Life Measurements of Bare, Mass-Resolved Isomers in a Storage-Cooler Ring

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Secondary beams from fragmentation of ^{58}Ni have been produced with energies of (200–220)A MeV, separated with a fragment separator and injected into a storage-cooler ring for half-life measurements. The relative momentum spread $\Delta p/p \approx 1 \times 10^{-6}$ (FWHM) which we achieved allowed us to resolve the ground and isomeric states of cooled ^{52}Mn and ^{53}Fe nuclei in the measured mass spectra. The circulating beams were fully ionized, which rendered it possible to measure *pure* β^+ branches for ^{52g}Fe and ^{53g}Fe and the sum of pure β^+ and γ branches in the decay of the isomers ^{52m}Mn and ^{53m}Fe.

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The β-decay probability of a nucleus is significantly affected by its ionic charge state. Striking examples are orbital electron capture (EC) which depends simply on the density of all bound electrons at the site of the nucleus, or the recently observed bound-state β^- decay of ^{163}Dy [1]. The number of bound electrons has implications for nucleosynthesis that occurs in stellar plasmas at high temperatures where a high degree of ionization prevails. Until recently such phenomena have been studied in highly ionized atoms including hydrogenlike ones [2–4], but not in bare ions. Bare radioactive nuclei can be generated by projectile fragmentation at relativistic energies, separated in flight and subsequently injected into a storage-cooler ring, where the specific decay properties can be studied over many hours.

In this Letter we report on half-life studies of fully stripped ions from fragmentation of ^{58}Ni beams. In several cases, β^+ decay was disentangled from the competing EC branch which can lead to drastic changes in the half-life. For the example of bare ^{52}Fe, an increase of the half-life by more than 50% with respect to the neutral atom was observed. Furthermore, by virtue of the experimental storage ring ESR [5] as a precision mass spectrometer, the ground and isomeric states of ^{52}Mn and ^{53}Fe were mass resolved and the corresponding half-lives were determined separately.

Experiments with secondary nuclear beams at relativistic energies are performed at GSI with the heavy-ion synchrotron SIS [6], the fragment separator FRS [7], and the storage ring ESR. The most attractive tool in the ESR is an electron cooler that drastically increases the phase-space density of circulating beams offering unprecedented conditions for precision experiments.

In a first experiment with stored and cooled ^{20}Ne fragments we recently demonstrated the potential of cooled secondary beams to measure half-lives and masses of light nuclides [8]. In the present experiment we have studied fragments in the $A \approx 50$ mass region with improved mass resolution.

The fragments were produced by a (360–380)A MeV ^{58}Ni beam in a 4 g/cm^2 beryllium target placed at the entrance of the FRS (see Fig. 1 of Ref. [8]). The primary energy was chosen such that the magnetic rigidity of the nuclei injected into the ESR was always fixed at 4.5 T m corresponding to (200–220)A MeV.

The FRS [7,9] was operated as a pure magnetic rigidity analyzer in order to transmit several nuclei with similar mass-to-charge ratios M/q. This procedure has some advantages: for mass measurements, nuclei with known masses contained in the fragment mixture can serve for calibration purposes; for half-life measurements, the method allows the half-lives of a series of nuclei to be measured simultaneously.

In the ESR electron cooling is applied to reduce the relative momentum spread of the stored fragment beam. With electron densities of typically 10^6/cm^3 a relative momentum spread of $\Delta p/p \approx 10^{-6}$ can be achieved. Because of the cooling process, the mean velocities of all fragments are the same. The lengths of the closed orbit and, consequently, the revolution frequencies depend on the mass-to-charge ratio M/q, and the frequencies can be measured by Schottky noise spectroscopy.

The Schottky technique is based on current signals induced at pickup electrodes by the circulating ions [10]. The revolution frequency (in our experiment we used the 21st harmonic) was mixed with an external frequency to shift the frequency band to the range of 0–100 kHz before being processed by fast Fourier transformation. Examples of Schottky spectra are presented in Fig. 1 for the case of ^{52}Mn and in Fig. 2 for fragments with $A/Z = 2$.

For cooled beams, the Schottky spectra exhibit well-resolved peaks corresponding to the different M/q values of the fragments. The separation of two neighboring peaks in the frequency spectra, Δf_{12}, is related to the

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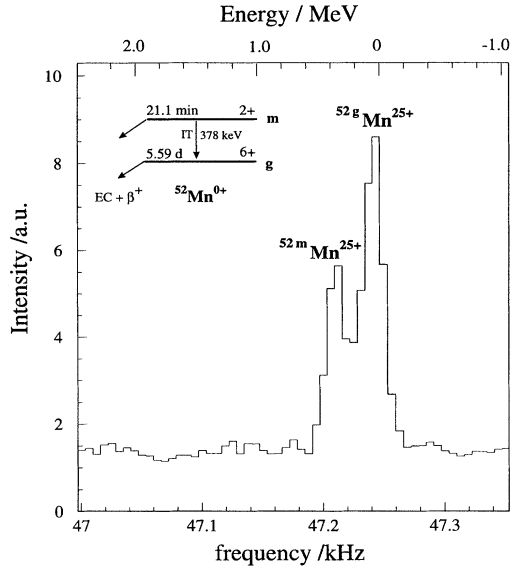

FIG. 1. Schottky spectrum of fragments stored and cooled in the ESR, recorded at the 21st harmonic of the revolution frequency and averaged over 40 s. The frequency scale denotes the difference to an admixed external frequency of 33.15 MHz. The mass-resolved lines of the ground and isomeric states ($E^* = 378$ keV) of bare ^{52}Mn show a width of 21 Hz (FWHM), corresponding to a relative momentum spread of $\Delta p/p = 1.2 \times 10^{-6}$. The partial decay scheme shown corresponds to neutral ^{52}Mn [11].

M/q difference by

$$\frac{\Delta f_{12}}{f_1} = -\frac{1}{\gamma_t^2}\frac{\Delta(M/q)_{12}}{(M/q)_1}, \qquad (1)$$

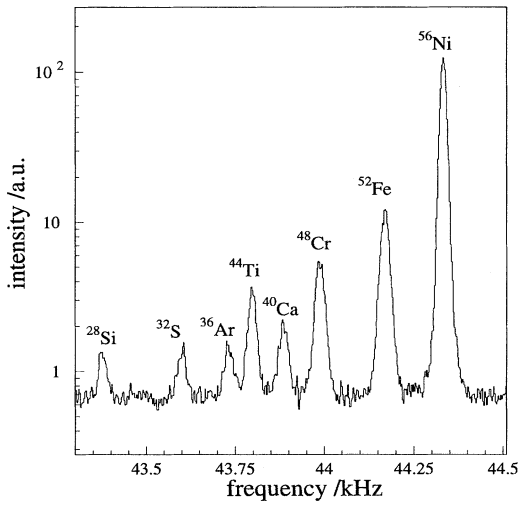

FIG. 2. Frequency spectrum of bare $A/Z = 2$ fragments, averaged over 1 min and recorded about 15 min after injection when the shorter-lived odd Z nuclides had decayed. The resolution is similar to that of the spectrum shown in Fig. 1.

where γ_t is an ion-optical parameter characterizing the operation mode of the ESR. In our case we used an ion-optical setting with $\gamma_t = 2.6$. The width Δf_1 of a single peak in the frequency spectrum is determined by the velocity spread Δv_1 of the corresponding ion via

$$\frac{\Delta f_1}{f_1} = \left(1 - \frac{\gamma^2}{\gamma_t^2}\right)\frac{\Delta v_1}{v_1}, \qquad (2)$$

where γ is the Lorentz factor. The masses of two nuclei can be resolved if $\Delta f_{12} > \Delta f_1$.

Since our first experiment [8] the mass resolution has been improved by a factor of 6 to a value of $\Delta M/M = 4 \times 10^{-6}$ so that ^{52}Mn and ^{53}Fe ground and isomeric states can now be resolved. Figure 1 demonstrates that this is possible even for ^{52m,g}Mn, where the isomeric state is only 378 keV higher than the ground state.

From the areas of the doublets in the Schottky spectra, the production ratios in the fragmentation reaction for the isomeric and the ground state, σ^m/σ^g, can be derived. For ^{52m,g}Mn (where the isomer has a low spin of $I = 2$ compared to $I = 6$ for the ground state) the result is $\sigma^m/\sigma^g = 0.62(3)$. For ^{53m,g}Fe (where the isomer is a high-spin state with $I = 19/2$ and the ground state has a spin of $I = 7/2$) we obtain a much smaller value of $\sigma^m/\sigma^g = 0.106(5)$. This indicates a preference for low-spin states to be populated in high-energy fragmentation.

In Fig. 2 we show a frequency spectrum of bare fragments with $A/Z = 2$. This spectrum was recorded 15 min after injection, so that short-lived nuclei have already disappeared. Taking the nuclides ^{44}Ti and ^{56}Ni as references, i.e., assigning to the corresponding peaks absolute masses from the compilation of Audi and Wapstra [12], the masses of ^{40}Ca, ^{48}Cr, and ^{52}Fe can be determined. The resulting values agree within an error of 20 keV with those given in Ref. [12] (quoted errors $\leq$10 keV). In this analysis the total energy of all bound electrons was taken into account. Since the separation in this $A/Z = 2$ cut directly reflects the nuclear binding energy, effects such as the inversion of ^{40}Ca and ^{44}Ti due to shell closure are visible. The mass calibration yielded for the mass difference between the ground and isomeric states of ^{52}Mn^{25+} (Fig. 1) a value of 363 $\pm$ 20 keV, in good agreement with the literature value of 378 keV [11].

By using *fully ionized* fragments it is possible, for the first time, to study the β^+ decay alone. Note that under these conditions internal conversion (IC) of isomeric transitions is also impossible. To detect β^+ decay in the ESR, one can make use of the fact that the decay alters the ionic charge state q by one unit and, hence, changes the trajectory [1].

In this experiment, however, we recorded the areas of the Schottky frequency spectra of the *mother* nuclei as a function of time. As these areas (on a linear scale) are proportional to the particle numbers, the total half-lives (total decay probabilities λ_{obs}) of the corresponding ions can be determined. The total decay probability observed

in the laboratory λ_{obs} is composed of a beam-loss constant λ^* due to atomic interactions with cooler electrons and residual gas atoms, and, possibly, of a nuclear decay probability λ_{nuc}: $\lambda_{obs} = \lambda_{nuc} + \lambda^*$.

Since the *bare* ions $^{36}Ar^{18+}$, $^{40}Ca^{20+}$, $^{44}Ti^{22+}$, $^{48}Cr^{24+}$, and $^{56}Ni^{26+}$ in Fig. 2 are essentially stable with respect to nuclear decay, i.e., $\lambda_{nuc} \approx 0$, their observed decay constants λ_{obs} render directly the corresponding beam-loss constants λ^*. We assume that the measured values shown in Fig. 3 have a Z dependence of $\lambda^* \propto Z^x$. From a fit to the data of Fig. 3 we obtain $x = 2.02$ if we exclude the data point for $^{52}Fe^{26+}$. This value agrees fairly well with the quadratic Z dependence expected if radiative electron capture (REC) in the cooler is the dominant beam-loss process [13].

For $^{52}Fe^{26+}$, the fitted curve of Fig. 3 yields an interpolated value of $\lambda^* = 0.058(5)\ h^{-1}$. This value is subtracted from $\lambda_{obs}(^{52}Fe^{26+})$ to yield the β^+ decay constant in the laboratory system, $\lambda_{nuc}(^{52}Fe^{26+}) = 0.045(5)\ h^{-1}$, which has to be multiplied by the Lorentz factor γ [$\gamma = 1.235(1)$ for this case], in order to obtain the nuclear decay probability in the rest frame of $^{52}Fe^{26+}$, $\gamma\lambda_{nuc}$. From that number, $\gamma\lambda_{nuc} = 0.056(6)\ h^{-1}$, we obtain finally the β^+ decay half-life for $^{52}Fe^{26+}$ in its rest frame, $T_{1/2}^{exp} = (12.5^{+1.5}_{-1.2})$ h.

We deduced for all runs the corresponding γ from the terminal voltage U_{cool} of the electron cooler: $\gamma = 1 + U_{cool}e/m_ec^2$. The uncertainty in the absolute cooler voltage, including space charge effects, yields a relative error of $\Delta\gamma/\gamma < 10^{-3}$ and is therefore omitted in the error analysis.

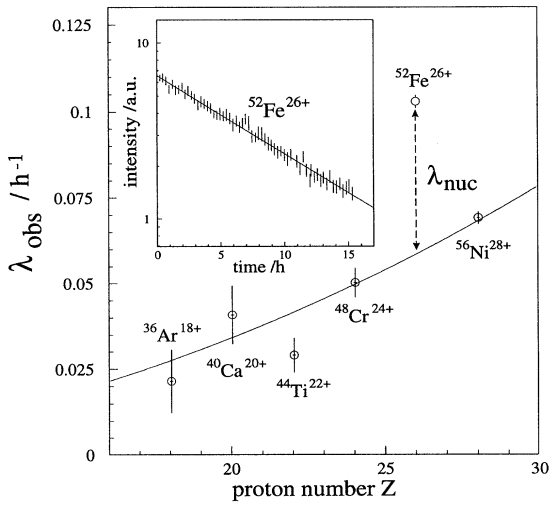

FIG. 3. Observed total decay constants λ_{obs} of stored bare ions from the $A/Z = 2$ cut (Fig. 2). The full line is a fit of a $\lambda^* \propto Z^x$ dependence for atomic beam losses to all data, except $^{52}Fe^{26+}$, which is the only isotope in the series where the nuclear decay constant λ_{nuc} is comparable to λ^* ($\lambda_{obs} = \lambda^* + \lambda_{nuc}$). The inset shows the decay curve of $^{52}Fe^{26+}$, observed over more than 15 h.

TABLE I. Literature values [11,14] of neutral-atom total half-lives, $T_{1/2}^{exp}$(neutral), half-lives of the corresponding bare ions, $T_{1/2}^{calc}$(bare), calculated according to Eq. (3), in comparison with experimental results from this work for bare ions, $T_{1/2}^{exp}$(bare).

Nucleus	$T_{1/2}^{exp}$(neutral)	$T_{1/2}^{calc}$(bare)	$T_{1/2}^{exp}$(bare)
^{52m}Mn	21.2(2) min	21.5(6) min	22.7(3.0) min
^{52}Fe	8.275(8) h	15.1(5) h	$12.5(^{+1.5}_{-1.2})$ h
^{53g}Fe	8.51(2) min	8.73(8) min	8.5(3) min
^{53m}Fe	2.58(4) min	2.58(4) min	2.48(5) min

Table I compares the experimental half-lives to those of the neutral atoms for ^{52}Mn (Fig. 1), ^{52}Fe, and ^{53m,g}Fe (Fig. 4). The table includes furthermore the expected half-lives of the bare nuclei derived from available spectroscopic information. This calculated half-life of a bare nucleus in its rest frame is given by

$$T_{1/2}^{calc}(\text{bare}) = T_{1/2}\left(\sum(I_\beta/\epsilon_f) + \sum I_\gamma\right)^{-1}. \quad (3)$$

$T_{1/2}$ is the total half-life of the neutral atom, $\sum I_\beta$ and $\sum I_\gamma$ are the summed intensities per decay of all β^+ and γ branches, and $\epsilon_f = f^+(\text{neutral})/f^+(\text{bare})$ is the ratio of the β^+-decay Fermi function for neutral and bare atoms, respectively [15].

The decay curves for ^{53m,g}Fe are shown in Fig. 4. Whereas the decay of ^{53m}Fe shows only a single component, the decay of ^{53g}Fe also contains feeding by the isomeric transition. Therefore the half-life of ^{53g}Fe was obtained in a separate run after the isomer had decayed.

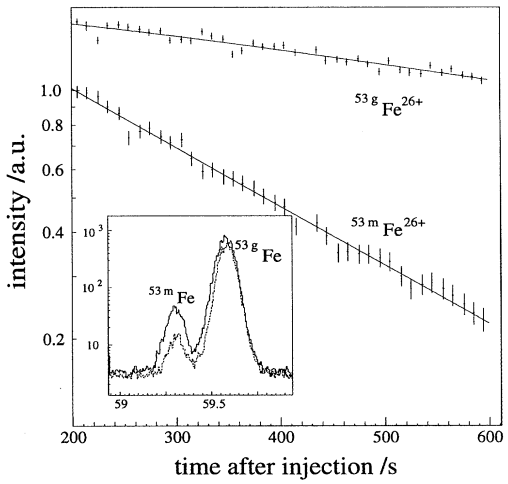

FIG. 4. Schottky peak areas of ^{52m,g}Fe as a function of the time after injection. The inset shows the Schottky spectra after 200 and 600 s. The mass resolution (FWHM = 760 keV) is sufficient to resolve the $7/2^-$ ground state and the $19/2^-$ isomeric state at 3040 keV excitation energy.

The results were then used to calculate the isomeric production ratio $\sigma^m/\sigma^g = 0.106(5)$ mentioned above, taking into account a 100% isomeric γ transition. With $\gamma = 1.227(1)$ the experimental half-lives $T_{1/2}^{\text{exp}}$(bare) given in rows 3 and 4 of Table I were obtained. In view of the short β^+ decay half-lives, the losses due to REC in the cooler were neglected.

The time dependence of the ^{52m,g}Mn Schottky peak areas was fitted by single exponentials, neglecting the weak ($\leq 2\%$) isomeric γ transition. The decay curve of $^{52g}Mn^{25+}$ with a neutral-atom half-life of 5.59 d is solely determined by REC in the cooler and therefore allows us to determine λ^* for this run. The resulting value together with $\gamma = 1.219(1)$ is then used to deduce for $^{52m}Mn^{25+}$ a half-life of $T_{1/2}^{\text{exp}}$(bare) = 22.7 ± 3.0 min.

For the cases of bare ^{52m}Mn and ^{53m,g}Fe the predicted half-lives $T_{1/2}^{\text{calc}}$(bare) from Eq. (3) are less than 4% longer than the values for neutral atoms, because the EC and IC branchings and the screening corrections are small. Within the uncertainties they agree with the experimental values $T_{1/2}^{\text{exp}}$(bare) listed in Table I.

This is not the case, however, for bare $^{52}Fe^{26+}$. For this isotope we have measured a half-life $T_{1/2}^{\text{exp}}$(bare) = $12.5^{+1.5}_{-1.2}$ h. From this we deduce according to Eq. (3) a β^+ branching of $I_\beta = 0.67(8)$ and an EC branching of $I_{\text{EC}} = 0.33(8)$ for the *neutral* atom, using the appropriate values for the half-life of the neutral atom [$T_{1/2} = 8.275(8)$ h], for the Fermi correction factor ($\varepsilon_f = 1.015$) and for the γ branch ($I_\gamma = 0$). This result differs significantly from the corresponding values quoted in the literature [11] [$I_\beta = 0.56(2)$, $I_{\text{EC}} = 0.44(2)$]. The latter numbers were *calculated,* however, from the adjusted Q_{EC} value of 2372(12) keV [12], by assuming that the ^{52}Fe ground state decays by 100% to the 1^+ level of ^{52}Mn at 546 keV. For such a simple case, there exists a unique correspondence between the Q_{EC} value and the β^+ ratio [15]. If we assume that the transition to the 1^+ level is the only decay channel, we get from our measured β^+ branching a value of $Q_{\text{EC}} = 2500^{+100}_{-90}$ keV, clearly in disagreement with Ref. [12]. A possible explanation for the discrepancy would be that the published level scheme [11] is incomplete, i.e., that additional β^+/EC decay channels must exist.

We have shown that the combination of the fragment separator FRS and the storage-cooler ring ESR provides a powerful tool for precise mass spectroscopy and lifetime measurements of exotic nuclei. Even more, it allows one to mass-resolve ground states and isomers and to obtain valuable information about specific decay branches.

For experiments of the type presented here, where the decreasing intensity of the stored mother nuclei is observed, beam losses due to atomic processes restrict the range of accessible half-lives to less than some hours. On the other hand, the need to first cool the unstable ions imposes a lower limit of about $T_{1/2} = 30$ s on nuclear half-lives that can be measured. Shorter half-lives limited only by the flight time of the fragments can be addressed when a monoisotopic beam from the FRS is stored in the ESR: in this case cooling is not essential to identify the stored isotope.

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