# Experiment Proposal for the FRS-ESR Facility at GSI

## Electron Screening and α–decay

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***Abstract*:** we propose to measure $Q_\alpha$-values and α-decay lifetimes of fully stripped heavy ions in order to get for the first time unambiguous determination of the electron screening energy. This is possible because changes in Q-value and lifetime are expected, with respect to the neutral atoms, due to the screening effect on the nucleus. In fact relative changes in the decay constant $\delta\lambda/\lambda$ have been calculated by some authors [1,2,14] to range from 20% up to 100%, depending on the $Q_\alpha$-value involved in the decay. We stress that at the present no measurement for such "bare" lifetime is available and the experimental facility FRS-ESR at GSI represents a worldwide unique opportunity to perform the proposed studies.

## 1. Introduction.

One of the open questions in nuclear astrophysics is the interpretation of the electron screening effects observed in low-energy nuclear reactions with light nuclei [3]. As pointed out by several authors [3-6] screening corrections deeply affect the reaction rates at low relative energies. Screening in the laboratory largely differs from plasma screening in stars forcing a double step procedure in extracting astrophysical reaction rates [4,6]. Therefore it is essential to clarify at least the screening effects on the measured cross sections.

The screening enhancement factor in charged-particle reactions at the astrophysical energies is usually written as $f(E) = \frac{\sigma_s(E)}{\sigma_b(E)} = \exp\left(\frac{\pi\eta U_e}{E}\right)$ [4], where $\sigma_s(E)$ and $\sigma_b(E)$ are the screened and bare cross sections of an arbitrary charged-particle reaction respectively, $\eta$ is the Sommerfeld parameter and $U_e$ the so called electron screening energy. In order to extract information on $U_e$, $\sigma_s(E)$ and $\sigma_b(E)$ must be determined. Large experimental sources of uncertainties for $\sigma_s(E)$ are due to the small reaction cross sections involved, the missing knowledge of stopping powers and the high accuracy needed in the knowledge of the relative energy between the interacting ions[4]. Concerning $\sigma_b(E)$, so far it can be evaluated by extrapolation or, at the best, by using R-matrix fit [5].

In this uncertain scenario one of the intriguing puzzles in nuclear astrophysics comes out, namely the discrepancy between experimental $U_e^{exp}$ and theoretical $U_e^{theo}$ values so far deduced. In particular, the $U_e^{\exp}$ values mostly exceed the maximum admitted theoretical ones and in some cases also by a factor two [4,8].

Since extracting information on $U_e$ by studying nuclear reactions at very low energy is very difficult we suggest here a completely different experimental method by simplifying, as much as possible, the system affected by the electron screening. It is well known since long time [1,7,9] that $Q_\alpha$−values and nuclear alpha-decay lifetimes should be different for bare nuclei from the neutral atoms, but till now these changes have been considered negligible. An interesting scenario appears when one deals with fully stripped emitters, since the inner electron shells play there a key role because of the large binding energies involved [2]. Infact, relative changes in lifetime are expected by some authors to range up to 100%, compared to the neutral case [1]. Details on the variation of nuclear decay rates are reported in the Emery [10] and Dostal, Nagel and Pabst [11] reviews.

Concerning the astrophysical implications, alpha-decay rates are also important for the determination of the r-process abundances of elements with A>206 AMU, including the cosmochronometers U and Th [12], and for determining the end point of the rp-process [13].

Already in the pioneering experiments with the combination of the FRS and the ESR Q-values and half-lives of bare and few electron projectile fragments have been measured for projectile fragments decaying via weak interaction [24]. The stored mother and daughter nuclei can be measured in different experimental scenarios depending on the difference in magnetic rigidities. If the half-live of the selected α-emitters and their daughters are a few seconds or longer, the combination of stochastic and electron cooling [30] can be applied and both mother and daughter nuclei circulate in closed orbits, allowing time-correlated Schottky analysis [22,31].

It is our aim, with the present proposal, to start a campaign of measurements devoted to the investigation of the alpha-decay properties of highly charged emitters. The strategy we want to pursuit can be summarized by the following points:

- $Q_\alpha$-values and α-decay lifetimes measurement of the "bare" emitters (present proposal).
- $Q_\alpha$-values and α-decay lifetimes measurement of one electron (H-like) and two electrons (He-like) alpha emitters.
- Lifetimes measurement of the neutrals species at the FRS focal plane.

The investigation of H-like and He-like emitters will give us information on the screening effects related with the inner K-shell. The lifetimes measurement of the neutrals will cross check and complement the existing data, sometime very old, found in literature, therefore establishing a solid reference data set, required to be conclusive about the expected evidence of lifetimes changes.

## 2. Theoretical prediction of $U_e$ and lifetime evaluation.

In order to introduce the theoretical approach for deducing the electron screening energy $U_e$ in heavy atoms, we consider here the sudden and the adiabatic limit of electron screening, as already reported in ref. [14].

In the sudden limit (giving the lower limit of $U_e$) one considers the value of the electrostatic potential at the nucleus due to the electrons. This is the average energy acquired by the alpha particle experiencing a static electric field produced by the "frozen" electron cloud at the nucleus. This electrostatic potential, deduced long time ago by Hartree calculations for the full range of atoms [15], can be parameterised by a power-law formula fitting the values tabulated by Dickinson [16], who reports non relativistic calculations. Relativistic corrections are not negligible in case of heavy nuclei and in ref. [2] we show for the first time the correct value of the sudden limit $U_e^{sl}$ :

$$U^{sl} = 2\left(\frac{12}{5}\right)Z^{7/5}R + 1.72665\cdot 10^{-3}Z^{10/3}. \quad (1)$$

Here $R$ is the Rydberg constant in energy unit ($R$=13.595 eV) and $Z$ is the charge of the daughter nucleus. This parameterisation has been obtained by fitting the relativistic Hartree-Fock-Slater calculations performed by Feiock and Johnson [17].

It is interesting at this stage to remark how, in case of alpha-decaying nuclei, $U_e^{sl}$ spans from 20 keV up to 40 keV, i.e. about 1% of the $Q_\alpha$ energy and it is $10^3$ times larger than the typical $U_e$ changes due to the chemical environment.

The adiabatic limit (giving the upper limit of $U_e$) can be deduced by considering the difference in the total electron binding energies of the parent atom $E_B(Z+2)$ and the daughter one $E_B(Z)$:

$$U_e^{al} = E_B(Z+2) - E_B(Z), \qquad (2)$$

with $E_B$ [18] parameterised as a function of the charge number $Z$:

$$E_B(Z) = 14.4381 Z^{2.39} + 1.55468 \cdot 10^{-6} Z^{5.35} eV$$

The trend of equation (2) is shown in Fig. 1.

A numerical comparison between the two limits (1) and (2) shows negligible differences, i.e. $U_e^{sl} = U_e^{al} = U_e$. The physical meaning of this can be inferred by using the Hellmann-Feynman theorem if, like in our case, $Z_\alpha << Z_{parent}$ (refer to [15] for further details). We will not discuss here the important consequences of such a result, but we stress that in the statistical regime where many electrons are involved, one gets a single theoretical prediction for $U_e$, removing any ambiguity. This marks a big difference with respect to the light systems involved in low energy reactions since in presence of few electrons one has to deal with a complex few-body system where particle-particle correlations play a major role.

As a matter of fact, any experimental evidence of very large screening potential energies in case of heavy nuclei, as those actually found in low energy astrophysical relevant reactions, could have dramatic effects on the alpha decay systematic.

In the following, we will use formula (2) in order to deduce the value of the screening energy. Moreover this is consistent with the fact that alpha particle velocity is much lower than electron velocity $v_\alpha << v_e$, fully supporting the adiabatic interpretation.

The values of $U_e^{al}$ calculated for three alpha decaying nuclei, $^{222}$Rn, $^{212}$Po and $^{147}$Sm are reported in Table 1. The three systems have been selected for comparison on the basis of their different $Q_\alpha$ values, spanning all the allowed range.

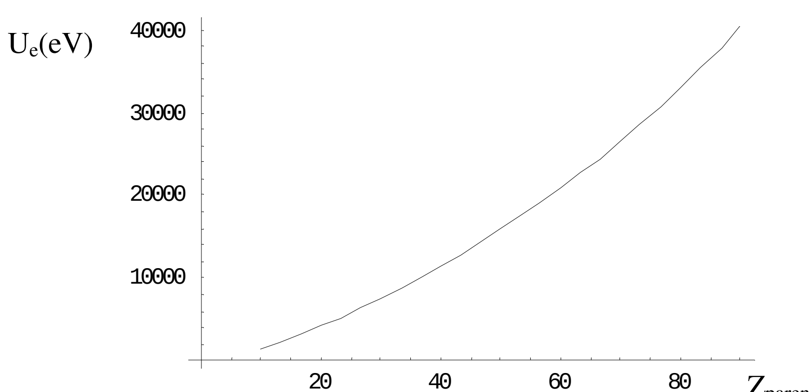


**Fig 1. $U_e$ screening energy potential vs $Z$ nuclear charge of the parent evaluated within the adiabatic limit.**

We will compute now relative variations of the α–decay constant λ by using the two models proposed originally by Erma [1] and Rubinson and Perlman [9]. The two approaches strongly differ each other and they lead to different theoretical estimations.
According to Erma the bare lifetime can be evaluated by the "artificial" change in the $Q_\alpha$-value which is completely equivalent to increasing the electrostatic barrier thickness [1]. Then one can deduce in a straightforward way the relative changes in the decay constants by using, for instance, the Coulomb penetrability written in terms of the regular and irregular Coulomb Functions as suggested in [2]. In Table 1 these changes are reported for the three different systems and they are consistent with Erma's and Liolios' expectations.

| Nucleus | $Q_\alpha(MeV)$ | $U_e^{al}(keV)$ | $\lambda_{scr}/\lambda_{bare}$ |
|---|---|---|---|
| $^{222}$Rn | 5.59 | 37.3 | 1.56 |
| $^{212}$Po | 8.95 | 35.8 | 1.21 |
| $^{147}$Sm | 2.31 | 21.9 | 2.17 |

**Table I. Screening energy $U_e^{al}$ and relative alpha-decay constants $\lambda_{scr}/\lambda_{bare}$ calculated in the adiabatic limit.**

In the case of bare $^{147}$Sm, due to the small $Q_\alpha$-value, a change by a factor two in lifetime is expected. This is a peculiar case, hardly accessible experimentally, because of the very long lifetime involved ($T_{1/2}=10^{11}$ years).

In the second model proposed by Rubinson and Perlman [9] is stated that on the assumption that $U_e$ is rigorously constant in the range $R \le r \le r_t$, where $R$ is the nuclear radius and $r_t$ the classical turning point, any non zero value of δλ will be wrong. This can be also expressed by the general remark that adding a spatially constant value to the potential cannot change the dynamics of the system. Consequently they derived a formula taking into account the slight radial dependence of $U_e$ in the range $R \le r \le r_t$. This can be worked out within a model of constant electron charge density in the volume bounded by the nuclear surface and a sphere of radius $r_t$. We will not report here the development of the theory [9], instead we will use the final result in order to deduce relative decay constant variations.

$$\Delta\lambda/\lambda = 4000 \cdot (Z-2)^3 E^{-7/2} \rho_e \quad (3)$$

where $Z$ is the nuclear charge of the parent nucleus, $E$ and $\rho_e$ are the energy of the emitted α–particle and the electron density at the nucleus respectively, both in atomic units.
By substituting in (3) the decaying properties of $^{147}$Sm, the most favourable case, and the electron density at the nucleus $\rho_e$ [9] we obtain a $\delta\lambda/\lambda \approx 10^{-3}$. Thus, two interesting scenarios come out. In particular, in the second case no change in the lifetime should be detected within the experimental errors, vanishing any possibility to change drastically α-decay lifetime by any modification of the *static* electron configuration inside and outside the atom. Nevertheless, in both the scenarios a change of $Q_\alpha$-value in the decay of the bare and the screened systems should appear, leading to the straightforward relationship $U_e^{sl} = Q_\alpha^{bare} - Q_\alpha^{screened}$ [19].

## 3. Experimental method.

We propose two ways to get ultimately experimental information on the electron screening effect in alpha decay:

- Measuring bare lifetimes, thus deducing $U_e$ through the Coulomb penetrability.
- Measuring bare $Q_\alpha$–values and comparing them with the atomic ones.

The combination of the fragment separator FRS [20] and the cooler-storage ring ESR at GSI [21] is a worldwide unique facility, which would allow for experimental investigation of the discussed topic.

### 3.1 Lifetime determination of bare nuclei.

We propose to use time-resolved Schottky mass spectrometry (SMS) [22,23] in order to measure the lifetimes of bare $^{212}$Rn, $^{213}$Fr and $^{220}$Fr nuclei.

All of the proposed nuclei are known to be merely alpha decaying nuclei and they can be produced in the projectile fragmentation reaction with the required intensity (larger than $10^2$ pps) due to rather large production cross-sections of uranium projectiles. Table II summarizes their known decay properties, calculated screening energy and expected relative decay-constant changes according to the approach of Erma.

| Nucleus | $T_{1/2}$ | $\alpha$–Branch (%) | $Q_\alpha$(MeV) | $U^{al}$(keV) | $\lambda_{scr}/\lambda_{bare}$ |
|---|---|---|---|---|---|
| $^{213}Fr^{87+}$ | 34.6 s (*3*) | 99.45 | 6.905 | 38.0 | 1.40 |
| $^{220}Fr^{87+}$ | 27.4 s (*3*) | 99.65 | 6.801 | 38.0 | 1.40 |
| $^{212}Rn^{86+}$ | 23.9 m (*12*) | 100 | 6.385 | 37.3 | 1.44 |

**Table II. Decay properties of the selected nuclei.**

The SMS is ideally suited for measuring half-lives in the range from about a few seconds to a few ten minutes. Thus, the lifetimes lie in the optimal range in which such Schottky half-life measurements are well established [24-26]. In the case of $^{212}$Rn, due to the longer lifetime involved, it will not be possible to neglect the unavoidable beam losses in the machine due to atomic charge changing in the electron cooler or the residual gas. In this case $\lambda_{loss}$ correction has been evaluated to be of the same order of magnitude as the expected $\lambda_{exp}$. Therefore it will be mandatory to deduce experimentally $\lambda_{loss}$ by measuring the lifetimes of nearby stable or long-lived species circulating simultaneously in the ESR, e.g. of the daughter nucleus $^{208}Pb^{82+}$. A similar technique has been previously applied in order to deduce $^{207}Tl^{81+}$ $\beta$–decay constant [26].

The constraints due to the time-range for applying the SMS (30 s < $\tau$ < 30 min) determine a narrow range of the $Q_\alpha$-values from 6.3 to 6.9 MeV to be accessed in the experiment. Moreover, the small range of nuclear charges involved (Z=83-86) restricts the range of electron screening energy $U_e$. As a result, one gets a narrow range for the expected $\Delta\lambda/\lambda$ variations as confirmed by Table 2.

As stated in the introduction, in future it would be important to perform measurements on one electron (H-like) and two electrons (He-like) alpha emitters in order to eventually reveal the expected strong effects of the inner K-shell on the decay.

The secondary bare ions will be produced by using projectile fragmentation of $^{238}U$ on a Be target (~1030 mg/cm$^2$ thick) and will be separated in the FRS by applying the so-called Bρ-ΔE-Bρ method [20]. For this purpose an Al wedge-shaped degrader will be used at the middle focal plane of the FRS (730 mg/cm$^2$ thick). In Table III the primary beam energy and the production cross-sections as given by the EPAX2 approximation [27] are reported. Intensities of injected beams into the ESR have been evaluated with the LISE++ [28] and MOCADI [29] codes. MOCADI calculations result in 10-15% less intensity. Prior to the injection into the ESR, identification of the selected species will be performed at S4, the achromatic plane of the FRS, by standard ΔE-TOF method.

| Bare Ion | $E_{lab}(^{238}U)$ [MeV·A] $10^9$ pps | $\sigma_{prod}$ [mb] EPAX | $E_{fra.}$ [MeV·A] | Bρ [T·m] | ESR Injected intensity [pps] |
|---|---|---|---|---|---|
| $^{213}Fr^{87+}$ | 550 | 2.6 | 399 | 7.762 | 2400 |
| $^{220}Fr^{87+}$ | 550 | 0.5 | 403 | 8.066 | 500 |
| $^{212}Rn^{86+}$ | 550 | 1.45 | 401 | 7.838 | 1350 |

**Table III. Expected production rates of secondary species as calculated by the LISE code.**

Selected "hot" fragments will be stored in the ESR where the stochastic pre-cooling, combined with the electron cooling, will be applied in order to reduce their velocity spread during a time interval of typically a few seconds [30]. Differences in A/q ratio between parent and daughter nuclei are in the range of 0.5 %, well within the ESR momentum acceptance of about 2.5 %. The momentum transfer ($\Delta p_{cm}$≈200 MeV/c) to the daughter, due to the alpha-decay, induces quite small velocity changes Δv/v(lab)≈0.15 %, therefore it should be possible to record the disappearance of a parent nucleus and the appearance of the daughter nucleus after a short cooling time (~0.2 s). Large betatron oscillations in the ring following the decay might induce losses of daughter ions. Since no data about in-ring mother to daughter transition are actually available for alpha decaying nuclei, we would like to perform a preliminary test in the regime of a few-particle injection (see beam time requirements for further details). In this way we will experimentally verify or disprove the post-decay permanence of the daughter ions in the ring.

In case of $^{220}Fr^{87+}$ the daughter ($^{216}At$) has a very short lifetime and α-decays into $^{212}Bi^{83+}$, which will then be observed with a difference in A/q ratio of about 1%.

In order to improve the reliability of the measurement we would like to perform the experiment in two different regimes:

- Injection of many particles into the ESR and integration of the frequency peak of the Fourier-transformed Schottky noise, following the spectra waterfall for both parent and daughter ions (many particles decay).
- Injection of a few particles followed by single particle decay-time measurements (single particle decay).

Both methods meanwhile represent standard lifetime measurements at the FRS-ESR [31]. As a matter of fact, the achievability of the present measurement in the case of $^{212}Rn$ has been verified in September 2002 in a different experimental context [30]. Unfortunately the measurement time was not long enough (Δt~60 s) in order to extract information relevant for our purpose (see Fig 2).

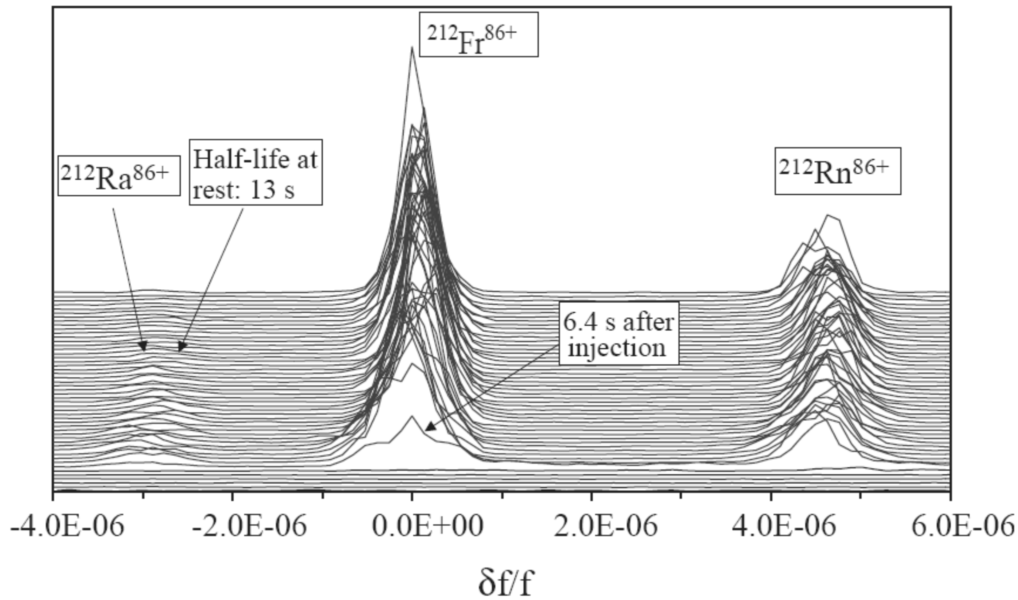


**Fig 2. Waterfall of Schottky spectra showing the isobaric mass triplet with $^{212}Rn^{86+}$ as already measured in September 2002 (from [30]) by applying stochastic cooling.**

In the single-decay measurements we avoid systematic uncertainties due to ring losses and contaminants by using parent-daughter time correlation, finally cross checking the obtained results. As mentioned above, the applicability of this method is submitted to the post-decay daughter survival in the ring, furthermore it is time consuming, due to the statistical sample needed.
Preliminary Monte Carlo calculations have been performed in order to estimate the number of ESR injections necessary to fulfil the required statistics for the case of single particle decays. In Fig. 3 the simulated decays, corresponding to a sample of $2{\cdot}10^3$ ESR injections of $^{213}Fr^{87+}$, are plotted. The injected parent distribution has been assumed to be Poissonian with an average of $\langle N\rangle=2$ (see Fig. 3a) and the total measurement time has been set equal to the expected bare lifetime in the lab frame $\tau = 70{\cdot}\gamma$ s where $\gamma$=1.429 (see Fig. 3b). Such low injection multiplicity is mandatory in order to disentangle each single parent decay (variation of the area of the Schottky frequency peak). Simulations performed for the other systems ($^{220}Fr^{87+}$ and $^{212}Rn^{86+}$) give similar results. The single-decay measurements appear impracticable only in the case of $^{220}Rn$ due to the long lifetime involved.

The statistical error on the extracted lifetime has been estimated to be 6% for both $^{213}Fr^{87+}$ and $^{220}Fr^{87+}$ nuclei by considering $2{\cdot}10^3$ ESR injections. In both cases this uncertainty leads to an error on the electron screening energy $\Delta U / U = 18\%$.

In conclusion the error on the deduced screening energy will be dominated by the systematic error due to $\lambda_{loss}$ evaluation in the case of $^{212}Rn$ and by the statistical errors in the cases of $^{220}Fr$ and $^{213}Fr$ nuclei. As shown by the Monte Carlo calculations, the measuring time will be mainly determined by the statistical sample needed by the single-decay method.

Beam time requirements are shown in the last section.

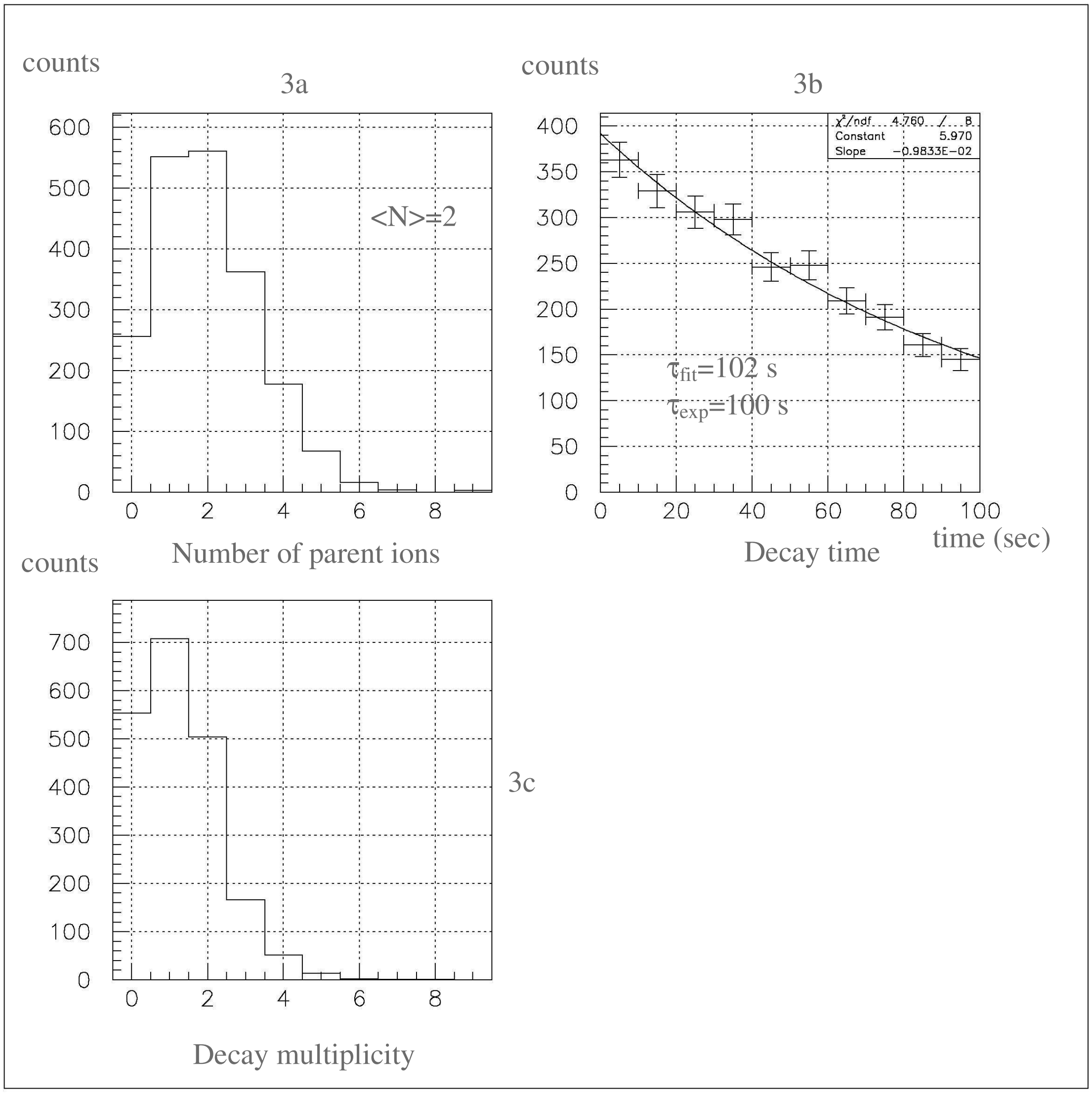


**Fig 3. Monte Carlo simulations for a sample of $2\cdot10^3$ injections of $^{213}Fr^{87+}$ into the ESR. (a) Initial Poisson distribution of parent ions. (b) Decay time spectrum. (c) Expected decay multiplicity per injection.**

### 3.4 Bare $Q_\alpha$ determination in ESR.

Bare $Q_\alpha$-value measurements in the ESR would allow a direct determination of the screening energy $U_e$ by comparison with the tabulated atomic $Q_\alpha$–values.
In order to accomplish this task, a resolution $\Delta Q/Q=10^{-3}$ is needed, which is at the limit of the actual ESR performance. Parent ($^{213}Fr^{87+}$ and $^{212}Rn^{86+}$) and daughter ($^{209}At^{85+}$ and $^{208}Po^{84+}$) nuclei must circulate in the ESR at the same time in order to record simultaneously Schottky frequencies for both species. The measurement can be performed at the same time as the bare lifetime determination. In this way, the masses of all circulating ions will be measured with the SMS, as is being done routinely at the FRS-ESR [22,23,31,32]. The $Q_\alpha$-value will be determined from the mass difference of the corresponding nuclides. Since the tabulated atomic masses cannot be used

directly for the calibration, we will use for this purpose the well-measured excitation energies of long-lived isomeric states, several of which will, as well, be stored in the ESR [22].

As already reported, it will not be possible for $^{220}Fr^{87+}$ parent nucleus to observe the daughter, but its decay product $^{212}Bi^{83+}$. In this case the bare Q-value=M($^{220}Fr^{87+}$)-2·$m_\alpha$–M($^{212}Bi^{83+}$) can be obtained and compared with the tabulated (atomic) one determining an electron screening energy $U_e^{tot} \cong 2 \cdot U_e^{220Fr}$.

## 4. Beam time requirement.

We would like to perform the proposed experiment in two separate runs:

1. FRS set-up and calibration, identification of mother nuclei at S4 (FRS), many-particles injection measurement, verification of post-decay daughter survival, preliminary $Q_\alpha$-determination.

2. Single particle measurements and the final $Q_\alpha$ measurement.

The analysis of the first run will give us necessary information about optimisations to be applied in the second run. Precise FRS calibration is mandatory to be confident about the ion species injected into the ESR.

In order to deduce the electron-screening energy of the selected alpha emitters with a relative error of 18% we need to analyse single particle decays in $2\cdot10^3$ ESR injections of $^{220}Fr^{87+}$ and $^{213}Fr^{87+}$ bare nuclei.

Thus, we ask for:

First run (1 shift=8 h) :

- 12 shifts for FRS setting, calibration and identification at S4(FRS).
- 9 shifts to perform many particles decay measurements for $^{220}Fr^{87+}$, $^{213}Fr^{87+}$ and $^{212}Rn^{86+}$ including 3 shifts for ESR settings.

Second run:

- 3 shifts for FRS-ESR setting.
- $2\cdot10^3\cdot$(120s + 120s)=17 shifts for the single particle measurement.

In summary we ask for a total of 41 shifts of $^{238}U$ at $E_{lab}$ of about 550 MeV/A (I=$10^9$ pps).

- 21 shifts, to be assigned to the first run
- 20 shifts, to be assigned to the second run

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