MEASUREMENT OF THE LIFETIME OF Pb^{52+}, Pb^{53+} and Pb^{54+} BEAMS AT 4.2 MeV PER NUCLEON SUBJECT TO ELECTRON COOLING

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ABSTRACT

By measuring the lifetime of stored beams, the recombination of the ions with cooling electrons was investigated. Rates found are larger than expected for radiative electron capture and significantly higher for Pb^{53+} than for Pb^{54+} and Pb^{52+}. These results are important for the design of the lead ion injection system for the Large Hadron Collider and for recombination theories.

When electron cooling [1] is applied to heavy ions, recombination - i.e. capture of cooling electrons into atomic levels resulting in losses of ions from the storage ring due to the change of their charge [2] - can become important. We have determined the recombination rates of partially stripped lead ions by storing and cooling beams from a recently commissioned linac [3] in the Low Energy Antiproton Ring (LEAR) (Table 1) to test its feasibility as a Low Energy Accumulator Ring for ions [4]. Rate coefficients were derived from the beam lifetime as a function of the electron current.

Table 1 - Parameters of the experiment

Ion energy	E	[MeV/u]	4.2
Velocity (of ions and electrons)	b = v/c		0.094
Storage ring circumference	$2\pi R$	[m]	78.54
Storage ring vacuum pressure	P	[torr]	$\approx 2 \times 10^{-11}$ (85% H_2 and He)

Cooling length/circumference	h		0.02
Electron beam radius	b	[cm]	2.5
Typical electron current	I	[A]	- 0.2 (0.4)
e-density in cooling section $n_e = I/e\pi b^2 bc$		[cm^{-3}]	1.1×10^8 I
Effective e-density per turn $n_{eff} = h n_e$ [cm^{-3}]			2.2×10^6 I
Typical longit. B-field in cooler	B	[T]	0.06

The linac accelerates Pb^{27+} [*] which is further stripped by a foil after the exit. A "dogleg" arrangement of bending magnets and a "momentum defining slit" are used to select a single charge state. The transfer line and LEAR have also to be readjusted to inject and store different states. About equal intensities of Pb^{53+} and Pb^{54+} and a slightly (~20%) lower current of Pb^{52+} were found, in fair agreement with the results of Ref. [5].

The intensity of the circulating beam in LEAR (about 2 μA corresponding to $\approx 5 \times 10^5$ ions at injection) was monitored via the Schottky noise [6], observed with current pick-up electrodes. A typical scan, giving the evolution of the beam current, is shown in Fig. 1. The 1/e lifetime (t) is obtained from an exponential fit. Decay rates (1/t) as function of the electron current are drawn in Fig. 2. From the slope of the curves, rate coefficients $a = <s v_{rel}> = (1/t)/n_{eff}$ (i.e. the decay rates normalised to the effective electron density h$_{eff}$, Table 1) are derived. They are collected in Table 2.

Table 2 -Rate coefficients. Present results and values reported in the literature for partially stripped uranium and gold ions. Included for comparison are the rates calculated for radiative capture from Bell's formula [7] taking an electron temperature $T_{e \perp}$ = 0.2 eV and an effective ion charge $Q_{eff} = (Q+Z)/2$ [8].

Ion	Measured rate coefficient a [10^{-8} cm^{3}s^{-1}]	Reference	Calculated from Bell's formula for radiative capture a [10^{-8} cm^{3}s^{-1}]

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[*] We use Pb^{Q+} to denote lead ions (atomic charge number Z = 82) of charge state Q, i.e. with Z-Q remaining electrons.

Pb^{52+}	11	present results (June 95)	2.25
Pb^{53+}	60	"	2.29
Pb^{54+}	9	"	2.32
U^{28+}	10	[8, 9, 11]	1.8
Au^{25+}	10	[9]	1.3

Two interesting facts emerge from this table: The rate coefficients are larger than calculated for radiative electron capture (using e.g. Bells' formula [7]) and the contrast between Pb^{53+} and the neighbouring charge states is very striking. The difference between Pb^{52+} and Pb^{54+} is not very significant given the error (±15%) of the measurement.

"Anomalously" high recombination rates have recently been found [8-11], with electron cooling or in a single pass technique with a co-moving "electron target", for a few special ions (Table 2). But this is the first time that neighbouring charge states of the same element were investigated with electron cooling showing a marked difference in the capture cross section.

Attempts reported in the literature to explain the "anomalous" recombination by dielectronic capture [2, 8-11] are so far only partially successful. Thus after a careful examination of the possible resonances Ref. [11] concludes that the "... recombination rate of U^{28+} ions... still remains a mystery." We have no explanation to offer for the higher rate of Pb^{53+} except the observation that Pb^{54+} and Pb^{52+} can perhaps arrange their remaining 28 and 30 electrons in closed shell structures (e.g. K, L, M shells for Pb^{54+}, K, L, M plus N, s-subshell for Pb^{52+}) whereas Pb^{53+} with its odd number of electrons does not have this possibility.

The motivation for the present study is the need for dense bunches of lead ions for the future Large Hadron Collider (LHC) [12]. Our results indicate that Pb^{54+} (or Pb^{52+}) is well suited for accumulation and electron cooling during a few seconds at 4.2 MeV/u, as proposed for the lead injection system of the LHC [4], whereas Pb^{53+}, originally foreseen, has an uncomfortably short lifetime in the presence of strong electron cooling.

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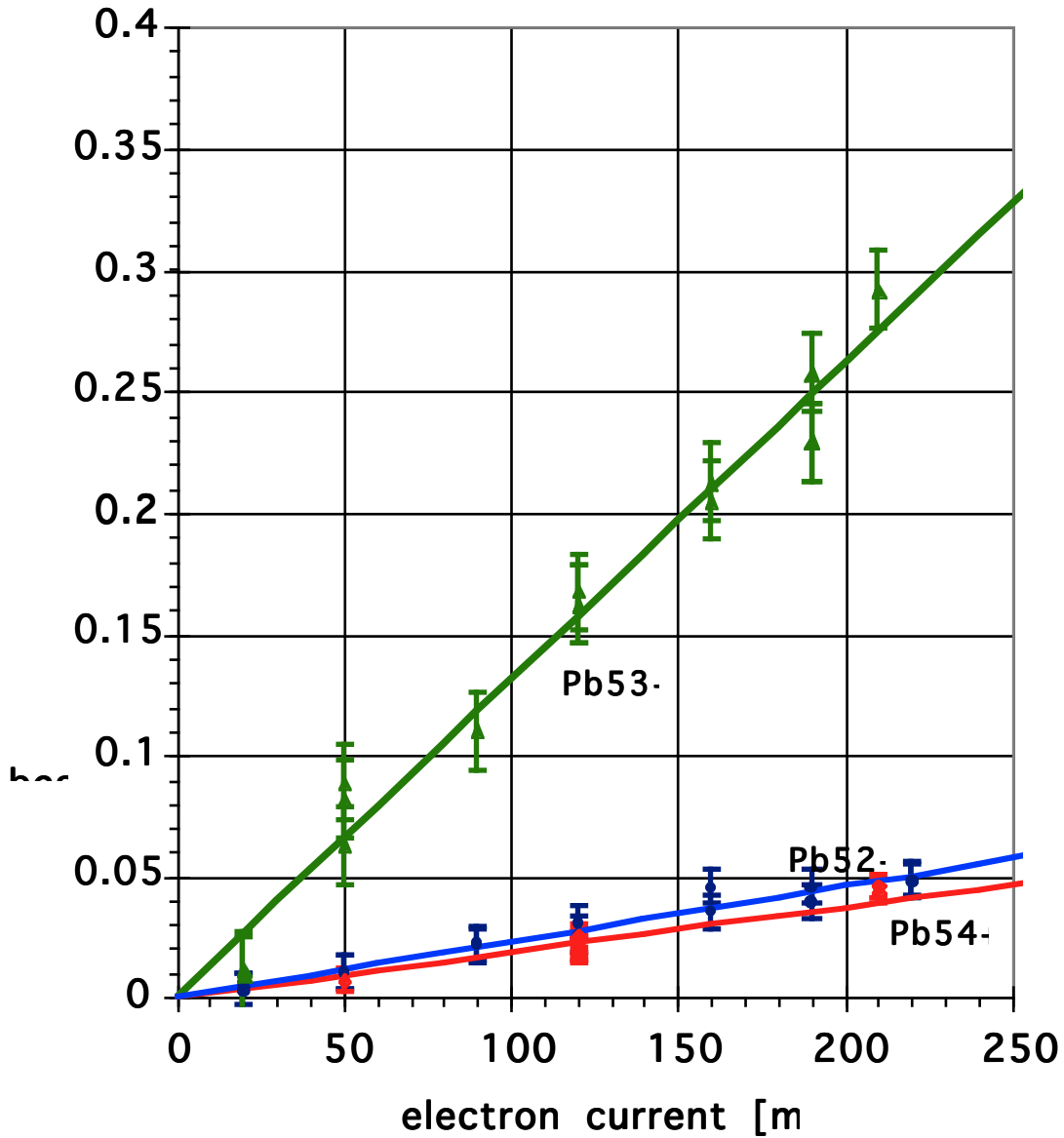
Fig. 1. Beam Schottky noise at the 100th harmonic (f ≈ 36 MHz) of the revolution frequency, as displayed by a spectrum analyzer used in the receiver mode to record the time evolution of the signal induced on a beam current pick-up electrode. The resolution bandwidth (30 kHz) of the analyzer is chosen to cover the full frequency spread given by the momentum width of the cooled beam i.e. the total noise in the band is recorded. The scan is triggered to start 0.2 s prior to injection and the evolution of the signal is shown during about 10 s. The electronic noise (N) of the acquisition system adds in square to the Schottky signal (S). Thus the voltage recorded by the analyzer is $U(t) = \sqrt{S^2(t) + N^2}$. The decay rate is deduced from an exponential fit of the Schottky power $S^2(t)$, which is proportional to the ion beam current. In this example the measurement for a Pb^{53+} beam at 120 mA electron cooling current is displayed.
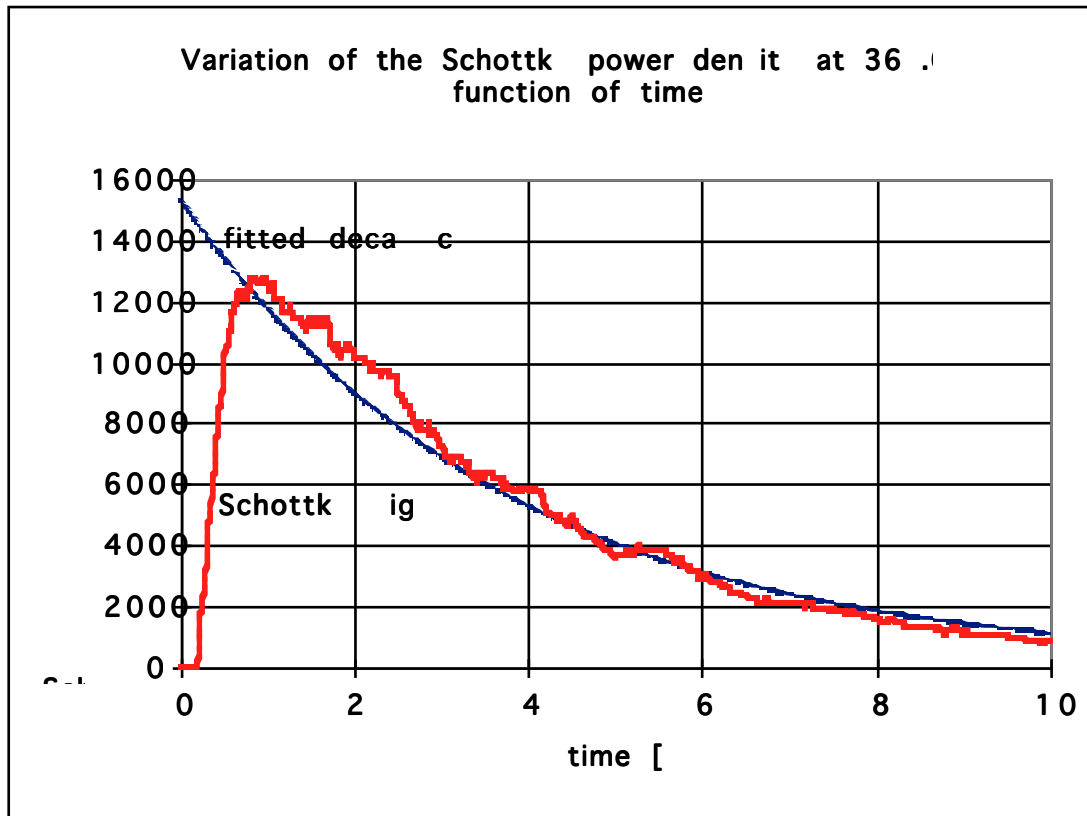
Fig. 2.Beam decay rates $1/t$ as a function of the electron cooling current. A constant "background" of $1/t \approx 1/20$ s, corresponding to charge exchange with the residual gas, has been subtracted from the data. The rate coefficients given in Table 2 are deduced from the slope of the curves.