Addendum to the ISOLDE Proposal IS466: Identification and systematical studies of the Electron-Capture Delayed Fission (ECDF) in the lead region

Part II: ECDF of ^{178,182}Tl

A.N. Andreyev , N. Bree, T. Cocolios, J. Diriken, J. Elseviers, M.Huyse,
P. Van den Bergh, P. Van Duppen, M. Venhart (*IKS, University of Leuven, Belgium)*
S. Antalic (*Comenius University, Bratislava, Slovakia)*
K. Nishio (*Advanced Science Research Center, JAERI, Tokai-mura, Ibaraki, Japan*)
U. Koster (*ILL, Grenoble, France*)
R.Page (*Oliver Lodge Laboratory, University of Liverpool, Liverpool, UK)*
I. Tsekhanovich (Manchester University, UK)
S. Franchoo (*IPN, Orsay, France)*
S.Vermote, C.Wagemans (*University of Gent, B-9000 Gent, Belgium*)
Martin Veselský (*Slovak Academy of Sciences, Bratislava, Slovakia*)
+ ISOLDE & RILIS

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In our recent successful experiment at ISOLDE (IS466, 31 May-6 June, 2008), a first unambiguous observation of the electron-capture delayed fission of the odd-odd isotope ^{180}Tl was performed. Few key ECDF properties have been measured for this decay, such as the ECDF probability P_{ECDF} for the parent nucleus ^{180}Tl and the energy (thus, mass) distribution of the fission fragments for the daughter nuclide ^{180}Hg, which also allowed us to deduce the total kinetic energy value (TKE). A surprising result – an asymmetric mass distribution of the fission fragments of the daughter ^{180}Hg was observed. This is in contrast to the symmetrical split in two semi-magic ^{90}Zr nuclei, which was expected before the experiment.

*The aim of the present addendum is to study this unexpected phenomena in more detail by extending towards the neighbouring odd-odd isotopes ^{178,182}Tl, for which the ECDF mode of decay is also expected based on the systematics and on our preliminary data from the IS466 experiment. Also this will provide important data on the isospin dependence of the ECDF properties in this new and very interesting region of the beta-delayed fissionning nuclei just below Z=82. In particular, these studies will supply unique **low-energy** fission data (e.g. probabilities, TKE release, fission barriers and their isospin dependence, mass/charge distribution of fragments, gamma multiplicities) for the region of the nuclei, which do not decay by spontaneous fission.*

I. General features of the electron-capture delayed fission (ECDF).

Both the general description and importance of the ECDF studies were presented in our original proposal IS466 [1], therefore, for consistency of the discussion here we will provide a brief reminder only.

Electron-capture delayed fission [2,3] is a rare nuclear decay process in which a parent (A,Z) nucleus first undergoes a EC decay, populating excited states in the daughter (A,Z-1) nucleus, which then may fission with some probability (Fig.1). ECDF is expected to occur with a detectable probability when the total Q_{EC}(A,Z) value of the *parent* nucleus is comparable with or greater than the fission barrier B_f(A,Z-1) of the *daughter* nuclide, see Fig.1. Then a certain branch of the parent EC decay can populate relatively high-lying excited states in the daughter nucleus which possess large fission widths (fission actually happens in competition with the gamma decay) [2]. It is important to stress that the excitation energy of the fissioning daughter nucleus is typically several MeV only, therefore ECDF provides unique fission data at low excitation energy, in which the shell effects might play a very important role.

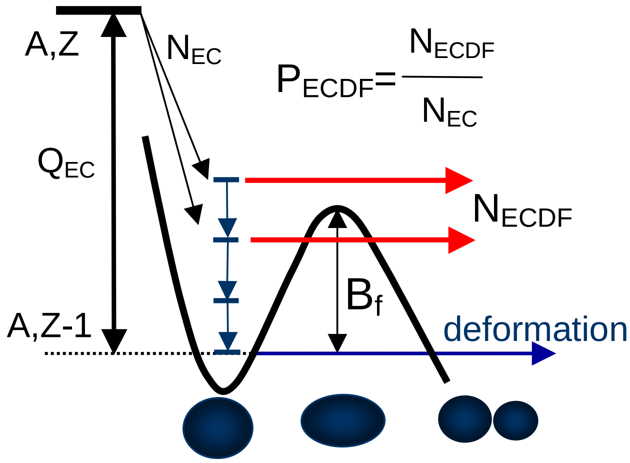

Fig.1(in color). Schematic diagram of potential energy versus deformation for the ECDF process. The parent nucleus (A,Z) undergoes an EC decay and populates excited states in the daughter (A,Z-1) nucleus, which might fission (in a competition with γ-transitions toward the ground state).

The probability of the ECDF, P_{ECDF} is defined as the ratio of the number of EC events resulting in fission, N_{ECDF}, to the total number of EC decays, N_{EC}:

$$P_{ECDF} = \frac{N_{ECDF}}{N_{EC}} = \frac{\int_0^{Q_{EC}} f(Q_{EC}-E) S_\beta(E) \frac{\Gamma_f}{\Gamma_f+\Gamma_\gamma}(E) dE}{\int_0^{Q_{EC}} f(Q_{EC}-E) S_\beta(E) dE}$$

, where the product of the integrated Fermi function $f(Q_{EC}-E)\sim(Q_{EC}-E)^5$ and the beta-strength function $S_\beta(E)$ accounts for the population of excited states in the daughter nucleus, while the ratio $\Gamma_f/(\Gamma_f+\Gamma_\gamma)$ describes the competition between γ-cascades leading to the ground state (gamma width Γ_γ) and fission (fission width Γ_f). The strong energy dependence of P_{ECDF} stems from the exponential variation of the fission width Γ_f for the sub-barrier fission, which allows to deduce the fission barrier B_f provided the P_{ECDF} value is measured and the $S_\beta(E)$ is either measured directly or calculated [1]. Both for $S_\beta(E)$ and for the Fermi function calculations, the knowledge of the Q_{EC} value is also required, that is why the direct measurement of the Tl masses in this region of nuclei is very important. In this respect, a feasibility of the mass measurements for ^{178,180}Tl will be discussed with the ISOLTRAP group. Furthermore, as a future project, we also consider a possibility to perform the experimental beta-strength function measurements for ^{178,180,182}Tl by using the TAS spectrometer of ISOLDE.

II. *Some preliminary results of the IS466 experiment*

The IS466 experiment was granted 18 shifts for measurements on ^{178,180}Tl isotopes and was successfully performed on 31 May-6 June 2008 by using the RILIS and the High Resolution

Separator (HRS). We note here that during the IS466 experiment we realised that the data being collected for ^{180}Tl decay were completely unexpected (see below). That is why we decided to spend most of the allocated beam time for the more detailed ECDF measurements for isotope ^{180}Tl and ask later for additional beam time for ^{178,182}Tl isotopes, the studies of which became especially interesting in view of the data measured for ^{180}Tl. Some of the results from the IS466 run are summarized below (the analysis is in progress, all data are preliminary):

- In total, approximately ~1200 singles ECDF decays of ^{180}Tl were detected, ~350 of which being observed as double-fold fission-fission coincident events, see Fig.2. A completely surprising result – an asymmetric energy (thus, mass) distribution of the fission fragments of the daughter nucleus ^{180}Hg was observed, which is in contrast to the symmetrical split in two semi-magic ^{90}Zr nuclei, which was expected before the experiment. (The asymmetrical mass split was the main reason for dedicating most of the allocated beam time to ^{180}Tl).

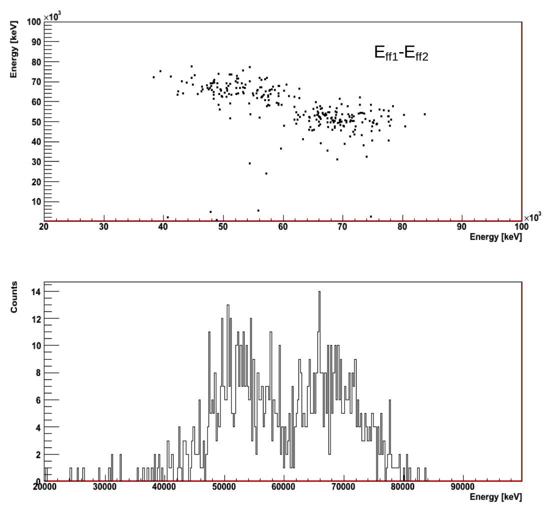

Figure 2: Top panel: the two-dimensional plot of coincident fission fragments for the daughter of ^{180}Tl – the nucleus ^{180}Hg. The energies E_{ff1} and E_{ff2} were measured in two Si detectors, see the scheme of the detection setup in Fig.4. Bottom panel – the projection on the energy axis from the spectrum in the top panel. Asymmetric energy (thus – mass) split is clearly seen in the Figure.

- A new ECDF branching ratio of P_{ECDF}=5(1)$\times$10^{-5} was deduced for the parent nucleus ^{180}Tl, which is much higher and much more precise than the previously estimated value of P_{ECDF}~10$^{-(7\pm1)}$ from study [3]. However, one should notice that the data from work [3] were always in doubts both due to the crude method used to deduced this value, and because this low value strongly deviated from the known smooth P_{ECDF} systematics in the actinide region. In constast, our new value, which was measured in a reliable way, fits well to these systematics.
- The 'rough' hyperfine structure scan (see Fig.3), performed by changing the frequency of the first excitation laser step of RILIS (in the broad-band mode) and simultaneously measuring the alpha-decay counting rate of ^{180}Tl at the detection setup, allowed us to draw a preliminary conclusion that the spin of ^{180}Tl must most probably be I=4 or 5. This is in contrast to the heavier Tl isotopes, in which typically the low-spin I=2 and the high spin I=7 long-lived ground and isomeric states are known. The change of the spin is due the change of the neutron orbital involved in the ground state of ^{180}Tl. Indeed, in ^{180}Tl (Z=81, N=99), the neutron $h_{9/2}$ orbital starts to be depleted for the first time, thus one expects a $[\pi s_{1/2}\times\nu h_{9/2}]_{4-,5-}$ configuration as the ground state in this nucleus. In the heavier Tl isotopes, either normal $[\pi s_{1/2}\times\nu i_{13/2}]_{6+,7+}$ or intruder $[\pi h_{9/2}\times\nu_{13/2}]_{2-}$ configurations were usually observed as the lowest in energy. The I=4 or 5 spin assignment for ^{180}Tl is also in agreement with the feeding pattern observed after the EC/β+ decay in the daughter ^{180}Hg, as we see strong feeding to the yrast 4^+ state along with a much weaker feeding of the 6^+ state.

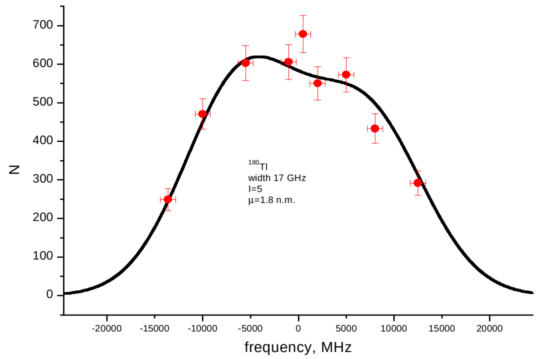

Fig.3 "Rough" HFS scan for ^{180}Tl, performed with the broad bandwidth laser in the first step. The fit by assuming I=5 spin is shown by the solid line. The I=4 spin assignment gives a similar fit, but a somewhat different amplitude ratios for the two expected peaks (seen in these rough scan as the 'left'-'right' components). In the present Addendum we propose to perform the more reliable spin determination for ^{180,182}Tl by performing the HFS scans with the laser tuned in the narrow bandwidth mode.

- The ISOLDE yields have been measured now down to ^{178}Tl, for which a yield of 0.2 ions/s was deduced for the first time. Importantly, our measured production yields for $^{179\text{-}182}$Tl were in a reasonable agreement with the values quoted at the ISOLDE web page [4] (but, see a comment on ^{180}Tl rate below). This, together with the following point (on the EC/β+ branching ratios) allows us to perform reliable estimates for the program proposed in this Addendum (see below).
- EC/β+ branching ratios were directly measured for the first time for $^{178\text{-}182}$Tl
- A first detailed α– and EC/β^+ decay study of ^{180}Tl will be possible from our data

These new data triggered an extensive collaboration with a number of theoretical groups in Europe, Japan and USA. The data analysis is underway and the results will be used for a master and a PhD thesis.

A remark concerning the production rate for ^{180}Tl should be made here. In the original proposal, we used an intensity estimate of ~610 ions/μC given at the ISOLDE web-site [4]. However, during the IS466 experiment the measured average yield was ~200 ions/μC. This was partly due to problems with the beam transmission through the recently installed ISCOOL setup at the HRS beam line used in our experiment. According to our measurements, the maximal transmission efficiency for the ISCOOL in our run was ~70%, while we had extended periods of running when the transmission was ~20% only. It also partly explains a somewhat lower fission rate for ^{180}Tl in comparison with our estimate in the original proposal. In this addendum, we propose to use the GPS separator, which should also provide a simpler and more reliable RILIS tuning and operation.

III. The proposed program: ECDF of ^{178,182}Tl nuclei

Based on new data from the IS466 experiment, we propose to extend the measurements to the neighbouring odd-odd nuclei – ^{178,182}Tl, for which the ECDF mode of decay is also expected based on the systematics and on our preliminary data from the IS466 experiment. In particular, during the short (~4 hours) yield test for ^{178}Tl, one fission decay was already observed for this nucleus, which is in an agreement with our expectations (see Table). Also, this short test showed that first detailed α-γ and EC/β+ studies of ^{178}Tl will be possible.

This work will provide important data on the isospin dependence of the ECDF properties in the new and very interesting region of the beta-delayed fissionning very neutron-deficient nuclei in the close vicinity to the shell-closure at Z=82. Furthermore, these studies will also supply unique **low-energy fission data** (e.g. probabilities, TKE release, fission barriers and their isospin dependence, mass/charge distribution of fragments, gamma multiplicities) for the region of the nuclei, which do not decay by spontaneous fission. The special features of the neutron-deficient Pb region (in comparison with the "classical" *deformed* actinide region, for which 10 ECDF cases are known so far) include:

- much larger Q_{EC} values, e.g. ~11.2 MeV in ^{178}Tl, to be compared to typical values of Q_{EC} ~4-5 MeV in the actinide region. This might also lead to the competition with the beta-delayed proton emission.
- much larger B_f values, e.g. ~9.3 MeV for ^{178}Tl, to be compared to typical values of B_f~5-6 MeV in the actinide region
- As a result of two above items, the larger and, importantly, *positive* Q_{EC} –B_f differences are expected for a number of nuclei in this region, e.g. Q_{EC} –B_f~2 MeV for ^{178}Tl. Therefore, one expects a substantial EC feeding well above the fission barrier in the daughter nucleus, which could result in high P_{ECDF} probabilities. Recently, in our experiment at SHIP, we saw this effect in ^{192}At, for which a value of P_{ECDF}~12% was determined, the highest ever value measured so far in any ECDF-decaying nuclei [5].
- On the other hand, a negative value of Q_{EC} –B_f~-0.5 MeV is expected for ^{182}Tl, thus altogether the Q_{EC} –B_f value of three isotopes ^{178,180,182}Tl will span the region from just below the fission barrier (^{182}Tl) to well above it (^{180,182}Tl).

It will also be important to investigate the possible role of the spin and configuration change of the ground state between ^{182}Tl on the one hand (where both $[\pi s_{1/2}\times\nu i_{13/2}]_{6+,7+}$ ground state and intruder $[\pi h_{9/2}\times\nu_{13/2}]_{2^-\text{-}11^-}$ configurations are expected) and the ground states of ^{178,180}Tl isotopes on the other hand (where the $[\pi s_{1/2}\times\nu h_{9/2}]_{4-,5-}$ ground state configuration is expected). In this respect, the HFS measurements with the narrow laser bandwidth will be important with the aim of the experimental spin determination of ^{178,180,182}Tl and possible isomerism, especially in ^{182}Tl.

For the proposed measurements we will use the same experimental set-up as for the IS466 experiment. The measured production yields of ^{178,180,182}Tl and expected fission yields for ^{178,182}Tl are given in the table and were calculated as $N_{fission}=N_{produced}\times b_{EC}\times P_{ECDF}$.

Table. Expected and measured (for ^{180}Tl only) fission rates for $^{178\text{-}182}$Tl (last column). The measured (preliminary) production rates for ^{178,180,182}Tl are from IS466 experiment. The (preliminary) b_{EC} values are from IS466 run. The P_{ECFD} values were estimated based on P_{ECDF} systematics (see [1]) and assuming a linear dependence of P_{ECDF} on the Q_{EC}-B_f value.

ECDF Parent ($T_{1/2}$)	Measured yield [ions/μC]	Q_{EC}-B_f [MeV]	b_{EC} [%] (IS466)	P_{ECDF}	$N_{fission}$ /day singles fissions
^{182}Tl (3.1s)	~2000	-0.5	~99	~8×10^{-6}	~ 100
^{180}Tl (0.7s)	~200	0.8	95	~$5(1)\times10^{-5}$ measured in IS466	~300 measured IS466
^{178}Tl (0.25s)	~ 0.2	~2	50	~5×10^{-3}	~15

To summarize, the whole program requires the following ISOLDE beams:

- 2 shifts for the set-up and beam tuning before the experiment.
- 12 shifts for ECDF studies of ^{178}Tl. The expected number of events will be enough for quite precise (~15%) P_{ECDF} and TKE measurements. A rough measurement of the fission fragments mass distribution might be possible for ^{178}Tl.
- 2 shifts for the HFS measurements for ^{178,180,182}Tl with the laser tuned to the narrow bandwidth and exploring the possible isomerism in ^{182}Tl.
- 9 shifts for ^{182}Tl. The expected number of events will be enough for P_{ECDF} and fission fragments energy/mass distributions and the TKE measurement.

Therefore, we request:

- **25 shifts for ECDF measurements for ^{178,182}Tl isotopes with the RILIS**

If the experiment is approved by the INTC, we will request the beam scheduling to be done together with the approved IS456 experiment (Po charge radii measurements), as both setups use the same target, ion source (RILIS) and detection systems. This would allow a more efficient operation both for ISOLDE and the experimental groups.

References

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[4] Isolde yield web page at www.cern.ch/isolde

[5] A.Andreyev et al., ECDF studies of ^{192,194}At – in preparation for publication (2008)