EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Probing the structure of yrast states in even-even ^{214,216,218}Po through fast-timing measurements following the β-decay of ^{214,216,218}Bi

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Abstract:

Po isotopes demonstrate a multitude of interesting phenomena, such as shape coexistence in the most neutron-deficient isotopes and the presence of high-spin spherical isomers around N=126. The structure of the Po isotopes is ideally suited to test the applicability of the seniority scheme across the long isotopic chain, spanning many neutron sub-shells both above and below N=126. While extensive studies of 8^+ isomers in neutron-deficient even-even Po isotopes were performed in the past, not much is known on them in the neutron-rich cases. Such isomers can arise from several configurations, e.g. $\pi(h_{9/2})^2$, $\nu(g_{9/2})^n$, an α cluster coupled to a ^{208}Pb core or even from a mixture of them. The lifetime measurements for the aforementioned 8^+ states (also for the other states of the yrast band, such as 2^+, 4^+, 6^+) can provide important information on $B(E2)$ values, which can then be used to test the different theoretical approaches and underlying configurations. Thus, the goal of this proposal is to perform for the first time lifetimes measurements of excited states in ^{214,216,218}Po via the fast-timing method following the β-decay of ^{214,216,218}Bi.

Requested shifts: 7 shifts (in a single run)

1 Physics Motivation

1.1 Introduction

Since long, nuclei in the vicinity of the doubly-magic $^{208}_{82}$Pb$_{126}$ represent crucial benchmarks for testing the predictive power of the nuclear shell model. In particular, Po isotopes having two protons above Z=82 are especially suitable for testing the seniority scheme across the long chain of isotopes, also spanning the N=126 shell closure. This can be achieved via e.g. fast-timing measurements of isomeric states and low-lying yrast states, which provide information on reduced transition probabilities, $B(E2)$. A large bulk of data on excited states and $B(E2)$ values for neutron-deficient Po isotopes exists in the literature [1]. These nuclei can be relatively easily studied through fusion reactions with heavy ions [2] or in Coulex experiments [3]. Several theoretical descriptions are available for the neutron-deficient region of nuclei along the Z=82 closed shell where phenomena like shape coexistence have been discovered and are of high interest [4].
In contrast to this, the studies of neutron-rich nuclei with Z > 82 and N > 126 are much more difficult, as only very specific techniques can be applied here. One of the methods to populate excited states in such nuclei is the use of multi-nucleon transfer reactions such as ^{18}O+^{208}Pb which was recently used to study ^{210,212,214}Po [5, 6, 7, 8, 9]. However, this method can only produce nuclei rather close to ^{208}Pb. To reach even more neutron-rich

nuclei, the use of high-energy fragmentation (at e.g. ISOLDE) is a method of choice (or, in inverse kinematics at FRS-like, [10]).
In order to understand the evolution of shell structure it is important to follow the trend along the long isotopic or isotonic series. This is, for example, the case for the study of the filling of the $\nu g_{9/2}$ orbital above N=126, which is expected to play the major role in $^{211-220}$Po.

1.2 Previous studies of even-even Po isotopes

As underlined in Refs. [5, 6, 7, 8, 9, 11], the low-lying levels in the even-even Po isotopes are governed firstly by the two-proton particle degrees of freedom (due to $\pi(h_{9/2})^2$) and secondly by the interaction of these two protons outside the Z=82 closed shell with the valence neutrons in different sub-shells. In particular, the N=126 closed shell nucleus ^{210}Po shows only the first type of interaction, and is thus a classical example of a doubly-closed shell nucleus plus two particles (^{208}Pb + 2p) . The energies of the yrast 2^+, 4^+, 6^+ and 8^+ states follow a seniority-like pattern of decreasing energy splitting between adjacent states with increasing spin, suggesting that the states belong to the $\pi(h_{9/2})^2$ multiplet.
The Kuo-Herling interaction was used to perform shell-model calculations for ^{210}Po [12] and has shown good agreement with the experimental energies proving that the two-proton excitations, such as the broken pair configuration $\pi(h_{9/2})^2$, are dominant for the 0^+ ground state and low-lying 2^+, 4^+, 6^+, 8^+ levels. A recent study [8] showed that the value of the 2^+_1 state lifetime in ^{210}Po is three times shorter than the adopted one. However, this finding was still not able to account for the discrepancy between theory and experiment previously known from shell model studies and which also appears in the QPM calculations. The study concludes that a more thorough theoretical investigation of this problem is required.

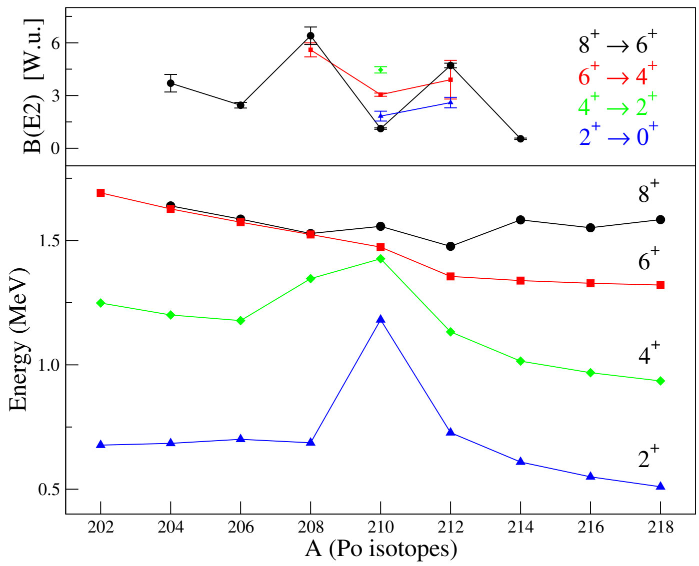

Figure 1: (Top) Experimental values of the reduced transition probabilities $B(E2)$ in the yrast band for even-even $^{204-214}$Po. (Bottom) Evolution of the first energy levels in the even $^{202-218}$Po isotopes. Data taken from [1, 8, 9].

Above N=126, the neutrons occupy high-spin orbitals such as $g_{9/2}$, $j_{15/2}$ and $i_{11/2}$; breaking these neutron pairs will lead to multiplet structures which will interact with the $\pi(h_{9/2})^2$ multiplet.
Recent findings [5] have shown that the structure around this region can involve different

types of excitations: states in ^{212}Po have been observed and were associated with configurations in which an α particle is coupled with a doubly-magic ^{208}Pb core. The excitations of the α+^{208}Pb cluster structures could mix with single-particle excitations and possibly explain the experimentally measured values where the first levels of ^{212}Po do not follow the trend of the heavier isotopes, even though the distance in energy between the 0^+ and the 8^+ states is almost the same. This variation is shown in the bottom part of Fig. 1.
The observation of high-spin states in ^{214}Po reported in Ref. [6] pointed out that their structure most likely involves breaking one and two pairs of nucleons in the four orbits above the magic gaps, $\pi h_{9/2}$ and $\pi f_{7/2}$, $\nu g_{9/2}$ and $\nu i_{11/2}$. The authors compared the excitation energy of the excited states of ^{214}Po to the ones of the neighbouring isotopes, shown in Fig. 1. It clearly shows a resemblance between the yrast structures of the ^{214,216,218}Po isotopes.
A deeper insight into the wave-function configurations of yrast states of heavy Po isotopes can be obtained by looking at the reduced transition probabilities, particularly the $B(E2; 8^+ \to 6^+)$ values which have been measured for even-even Po isotopes with A=204-214 and are shown in the top panel of Fig. 1.
One interesting feature that arises from Fig. 1 is the staggering of the $B(E2)$ values which does not have an obvious explanation to our knowledge. The large value measured in ^{212}Po was proposed to be due to the α+^{208}Pb cluster structures [5] mentioned earlier. Regarding ^{214}Po, the experimental $B(E2; 8^+ \to 6^+)$ value is of the same order of magnitude as the one of ^{210}Pb [1], the latter dominated by the ν^2 configuration. These values are also comparable with the one corresponding to ^{210}Po which is dominated by the π^2 configuration.
These observations indicate that a neutron-pair breaking is likely the main excitation process of the 8_1^+ state in the heavy Po isotopes. However, this assumption should be investigated further through the measurement of the $B(E2; 8^+ \to 6^+)$ in the heavier ^{216,218}Po, which is the main motivation of the present proposal. We also notice that a similar staggering, albeit with a reduced magnitude, is also seen for the 2^+, 4^+, 6^+ states, where B(E2) values are available. This is also a puzzling feature, not observed before. Our study will provide data for several such states in ^{214,216,218}Po.

1.3 β-decay studies of ^{214,216,218}Bi at ISOLDE

As shown in recent studies [11, 13], the high spin values (I > 6) [1] of the β-decaying states of ^{216,218}Bi allow the population of medium-spin states in ^{216,218}Po, with I^π up to 8^+. A β-gated γ spectrum from Ref. [13] is displayed in Fig. 2, showing the clear identification of the γ-rays in the decay of ^{218}Bi. The presently known β-decaying state in ^{214}Bi is a 1^-, although recently a high spin isomer was identified which populates the 8^+ state in ^{214}Po (IS608 experiment at IDS in 2017 [15]) as it is the case of the heavier Bi isotopes.
This opens the study of the yrast structure in ^{214}Po through β decay in a similar way as it was done for the heavier Po. The previous β decay studies of ^{214,216,218}Bi [6, 11, 13] clearly established their yrast structures (at least up to 8^+), although lifetime information is known only for the 8^+ in ^{214}Po [6].

According to the SM calculations based on the Kuo-Herling interaction [13, 12], the sequence of the 4_1^+, 6_1^+, and 8_1^+ states of ^{218}Po should be very compressed (as are those of ^{210}Po), at variance with the experimental results. This calls for a review of the realistic effective interactions to improve the predictions in this mass region. Understanding the underlying structure of the yrast bands of ^{214,216,218}Po and enhancing the systematics shown in Fig. 1 will help to better characterize the mixing between cluster configurations and single-particle excitations in the northeast region of ^{208}Pb. A better insight from the experimental point-of-view can be achieved through systematic lifetime measurements of the low-lying states of ^{214,216,218}Po populated in the β-decay of ^{214,216,218}Bi and furthermore by comparing the extracted $B(E2)$ values with calculations.

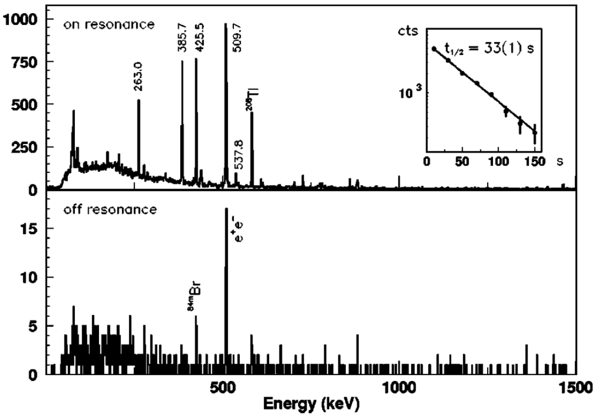

Figure 2: β-gated γ-ray energy spectrum at A=218 with (top) and without (bottom) laser ionization. The γ-peaks of which the energy is given (in keV) are attributed to the decay of ^{218}Bi which was produced in a UCx graphite target at ISOLDE and separrated using the General Purpose Separator (GPS). Figure taken from [13].

2 Experimental method

2.1 Beam production

The use of RILIS at ISOLDE allows at present to provide rather pure beams of Bi isotopes, as it was already shown in previous studies [16, 13] and in on-going hyperfine-structure measurements (IS608 [15] in 2016 at Windmill and MR-ToF MS, and 2017 at IDS). The main isobaric contaminants are the surface ionized Fr. However, for masses 214-218, the Fr isotopes are short-lived ($T_{1/2} < 22\,\text{ms}$) compared to the Bi isobars ($T_{1/2} > 33\,\text{s}$) such that this background can be significantly suppressed using the pulsed-release technique [17, 11] - a delayed opening of the electrostatic beamgate ($\Delta T = 20\,\text{ms}$ for ^{218}Bi as reported in Ref. [13]) relatively to the proton impact in order to suppress the short-lived activity and leave the long-lived activity mostly unaffected. As shown in Fig. 2 taken from the previous study of ^{218}Bi [13], a clean decay pattern can be derived by using β-γ coincidences.

The yields of Bi isotopes at ISOLDE were extensively studied in the past and summarized in Ref. [14]. Considering the latest upgrades of the RILIS system, better ionization efficiencies should be achieved, as indicated in [15]. Using the presently available Blaze Nd:YVO_4 laser with P=20W for the 3^{rd} excitation step, the efficiency increases to $\epsilon = 10\%$ compared to $\epsilon = 1\%$ [16] when using a P=1.5W laser. Therefore, the production yields of ^{214,216,218}Bi were measured to be greater than $2{\times}10^4$, $2{\times}10^3$ and $2{\times}10^2$ ions per second with an average 1.5 μA proton beam [15]. A slighly lower number of ions will arrive at IDS considering the beam transport efficiency of $\sim$80%. Taking into account also other

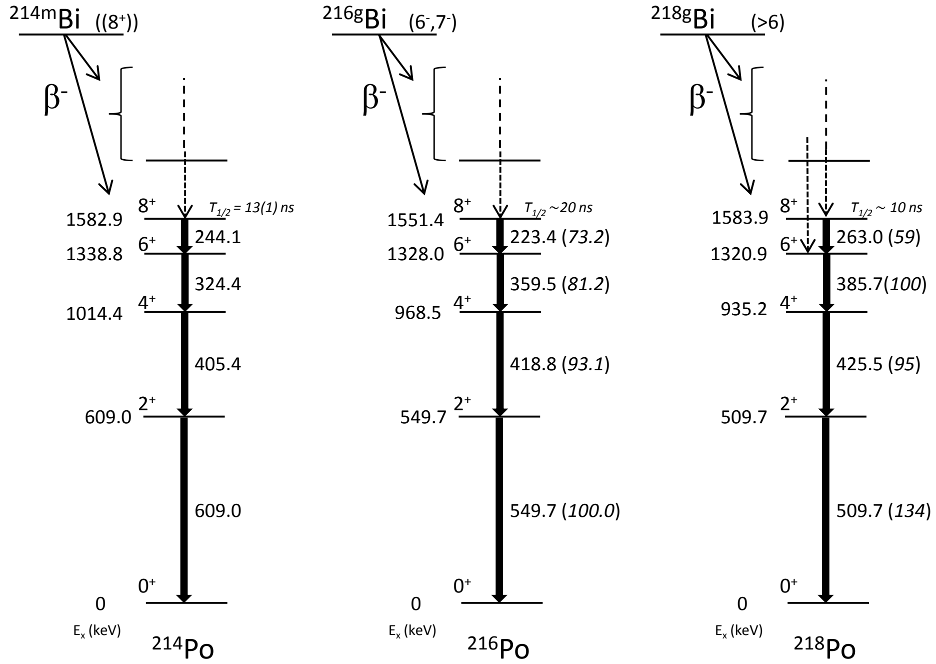

Figure 3: β-decay level schemes of ^{214,216,218}Po according to the ENSDF database, Ref. [11] and Ref. [13] respectively. The half-life of the 8^+ state in ^{214}Po is from Ref. [6] while for ^{216,218}Po the values are estimated [6], considering a similar $B(E2)$ value as in ^{214}Po. The relative intensity of each transition is indicated in brackets for ^{216,218}Po while in ^{214}Po there is no data available from β-decay.

losses (downtime from PSB and RILIS), we will therefore use a realistic effective rate of 10^4, 10^3 and 10^2 ions/second arriving at IDS of ^{214,216,218}Bi ions respectively.

2.2 Fast-timing at the ISOLDE Decay Station

The measurement of nuclear half-lives using the β-$\gamma(t)$, γ-$\gamma(t)$ and β-γ-$\gamma(t)$ fast-timing method [18, 19] is a well established technique [20, 21] at the ISOLDE Decay Station (IDS). It can cover a range of half-lives between 10 ps - 100 ns using fast-timing detectors such as $LaBr_3$(Ce) and plastic scintillators in coincidence with HPGe detectors. Even longer half-lives can be measured in the μs range using solely the timing information from the HPGe detectors. The absolute β and γ-ray detection efficiencies of IDS are roughly: 20% for β recorded in the fast plastic scintillator , 6% for γ-rays at 300 keV and 3% at 500 keV for the two $LaBr_3$(Ce) detectors, 9% at 300 keV and 7% at 500 keV for the HPGe detectors [22].
In the case of the ^{214,216,218}Po isotopes, the estimated half-lives of the yrast band levels are in the ranges accessible at IDS. By assuming, for ^{216}Po and ^{218}Po, the same value of the $B(E2; 8^+ \rightarrow 6^+) = 0.54(4)$ W.u. as in ^{214}Po [6], the half-lives of the 8^+ states were estimated as $\sim$20 ns and $\sim$10 ns respectively. For the 2^+_1, 4^+_1, 6^+_1 states, the lifetimes were estimated considering 10 W.u. as an upper limit for the $B(E2)$ values (see the top part of Fig. 1). These estimations are summarized in Table.1 and are well within the reach of

the IDS capabilities.

Table 1: Effective yield at IDS, transitions de-exciting the levels of interest and their half-life estimation (using $B(E2)$ values of 0.5 W.u. [6] for the $8^+ \rightarrow 6^+$ transitions and an upper limit of 10 W.u. for the other cases) and total statistics expected for the ^{214,216,218}Po isotopes using the γ_{LaBr}-γ_{LaBr}-γ_{HPGe} (for the 2^+_1, 4^+_1, 6^+_1 states) and β-γ_{LaBr}-γ_{HPGe} (for the 8^+_1 states) fast-timing methods. The absolute intensities of the transitions involved are indicated in Fig. 3, the ones corresponding to ^{214}Po were considered similar to the ones in ^{216}Po.

Nucleus/Yield	J^π	E_γ (keV)	$T_{1/2}$	Events/shift
^{214}Po	2^+_1	609.0	>9 ps	4.9×10^4
10^4 ions/s	4^+_1	405.4	>68 ps	9.5×10^4
	6^+_1	324.4	>210 ps	1.7×10^5
	8^+_1	244.1	13(1) ns [6]	7.7×10^5
^{216}Po	2^+_1	549.7	>15 ps	5.9×10^3
10^3 ions/s	4^+_1	418.8	>58 ps	9.7×10^3
	6^+_1	359.5	>120 ps	1.7×10^4
	8^+_1	223.4	~27 ns	7.6×10^4
^{218}Po	2^+_1	509.7	>21 ps	6.5×10^2
10^2 ions/s	4^+_1	425.5	>52 ps	1.1×10^3
	6^+_1	385.7	>86 ps	1.4×10^3
	8^+_1	263.0	~12 ns	6.1×10^3

The half-lives of the 8^+ states in ^{216,218}Po can be determined experimentally, in an ideal case (no isobaric contamination, low background), through the β-$\gamma(t)$ method by gating on β particles in the plastic scintillator as the START and the $8^+ \rightarrow 6^+$ γ-rays in the $LaBr_3$(Ce) detectors respectively as the STOP for the Time to Amplitude Converters (TAC). However, because of the possible Fr contamination, an extra gating condition will be required in the HPGe detectors in order to obtain a clean γ-ray spectrum for selecting the STOP gate. The transitions below the 6^+ level are suitable candidates for gating in the HPGe detectors and extract the timing information through the β-γ_{LaBr}-γ_{HPGe} method. The HPGe detectors efficiency when gating on any of the three transitions below the 6^+ level is 23% (sum of the three individual absolute efficiency values for the corresponding transitions).
The half-lives for the 2^+_1, 4^+_1, 6^+_1 in ^{214,216,218}Po can be extracted through two methods: (1) the β-γ_{LaBr}-γ_{HPGe} method offers increased statistics but will carry the half-lives of the intermediary levels into the final result, and (2) the γ_{LaBr}-γ_{LaBr}-(γ_{HPGe}/β) method which is more restrictive but will allow the independent half-life measurement of each level by looking at the timing information from the $LaBr_3$(Ce) detectors of γ-rays populating and de-populating each level in coincidence with either (a) any other γ-rays in the level scheme recorded by the HPGe detectors or (b) β particles in the plastic scintillator. Ideally, both methods (1 and 2) should be used in order to cross-check and verify the measured values.

3 Beamtime request

We propose the first fast-timing measurement of the ^{214,216,218}Bi β-decays in order to study lifetimes of yrast states in the Po daughters. As shown in the previous section, all the estimated half-lives of levels in the yrast bands are suitable candidates for measurement at IDS. The only constraint left is the total statistics in the time spectrum. A number of roughly 10^3 events should be sufficient to measure the required half-lives with a precision lower than 10%. Therefore, 2 shifts are requested for the fast-timing study of ^{218}Po, 1 shift for ^{216}Po and 1 shift for ^{214}Po. It should be noted that in fast-timing measurements, very high count-rates (more than 3-4 kHz / detector) are not desired due to pile-up effects, therefore the rate of incoming ^{214}Po ions will most likely be reduced to match the rates of ^{216}Po. An extra shift is requested for on-line fast-timing calibrations using implantation sources and two shifts for laser tuning.
It is worth mentioning that the IS608 experiment [15] dedicated, among others, to hyperfine structure (HFS) studies of neutron rich Bi isotopes was performed at IDS in 2017 and, due to production problems, still has 3 shifts left to finalize the measurement of ^{216,218}Bi. If the present proposal is accepted, the authors suggest planning the two experiments one after another because of two main reasons: (1) the IDS fast-timing configuration is suitable also for HFS studies (which require only γ-ray detection) and (2) the laser tuning will be performed only once for both measurements.
Summary of requested shifts:
We request a total of 7 shifts: 4 shifts for β decay fast-timing measurements of ^{214,216,218}Bi, 1 shift for online fast-timing calibrations and 2 shifts for laser tuning.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: (*name the fixed-ISOLDE installations, as well as flexible elements of the experiment*)

Part of the	Availability	Design and manufacturing
IDS fast-timing configuration	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed IDS installation.

Additional hazards:

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material [material]			
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		

• Sealed source	☐ [ISO standard]		
• Isotope			
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		
Dangerous for the environment	[chem. agent], [quant.]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			

Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): standard IDS usage