

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Clarification to the ISOLDE and Neutron Time-of-Flight  
Committee

**P-530: Investigation of Octupole Correlations in  $^{144,145}\text{Ba}$  using  
the Recoil Distance Doppler-shift Technique**

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**Abstract:** In this Letter of Clarification the following issues are elucidated as asked by the INTC with respect to our proposal P-530:

1. Discussion of the experimental parameters with respect to the use of incomplete fusion (ICF) to populate excited states of interest in  $^{144,145}\text{Ba}$  after  $^7\text{Li}$  breakup based on the available literature,
2. radiation safety issues especially regarding the long-lived decay product  $^{144}\text{Ce}$  that may accumulate within the beamline and the setup,
3. discussion of the fact that the beam intensity will be lower than foreseen in our proposal as was addressed by the TAC.

**Requested shifts:** 15 shifts (split into 1 run)

**Installation:** MINIBALL, Plunger device, CD + PAD detectors



# 1 The reaction mechanism: incomplete fusion

The aim of the proposed experiment is the investigation of the structure of neutron-rich  $^{144,145}\text{Ba}$  from absolute transition strengths with special respect to the occurrence of octupole correlations. Transition strengths will be determined from level lifetimes measured with the recoil distance Doppler-shift (RDDS) method using a plunger device newly developed by our group from Cologne that was already successfully used in experiment IS 628.

Here we aim to populate excited states in the nuclei of interest by incomplete fusion (ICF) of a radioactive beam with  $^7\text{Li}$  using a beam energy close to the Coulomb barrier. Due to the low separation energy of weakly-bound  $^7\text{Li}$  into a triton and an  $\alpha$  particle of 2.47 MeV a breakup of  $^7\text{Li}$  and a subsequent fusion of the reaction partner with the triton (or the  $\alpha$ -particle with a lower probability) takes place. A successive evaporation of neutrons will produce the nuclei of interest. As discussed in [Cla05] and references therein this experimental technique offers access to states up to about  $8 - 10\hbar$  in neutron-rich heavy nuclei with sufficient yield which are otherwise inaccessible by standard fusion-evaporation reactions. In [Jun02] even much higher angular momenta were detected in neutron-rich Dy isotopes, e.g., in  $^{160}\text{Dy}$  up to  $28\hbar$  where ICF was confirmed to play a very important role.

In addition, ICF is complementary to Coulomb excitation with radioactive beams as a stronger population of states with a relatively high angular momentum is likely after ICF and thus sufficient intensity of the corresponding  $\gamma$ -ray transitions for a RDDS analysis can be achieved. In this sense it should be stressed that the results of the recent experiment IS 553 on  $^{144}\text{Ba}$  at HIE-ISOLDE with Coulomb excitation in inverse kinematics by M. Scheck and coworkers yield that states with angular momenta  $> 4\hbar$  were only weakly populated or not observed at all.

This section is organized as follows: First we elucidate the feasibility of ICF of radioactive  $^{144}\text{Cs}$  projectiles with tritons after  $^7\text{Li}$  breakup in the plunger target for the production of the compound nucleus  $^{147}\text{Ba}$ . This is based on the literature available for such ICF reactions, where this information was derived mostly from stable beam experiments. In the following, we give arguments that under the chosen experimental conditions the evaporation of three or two neutrons from the ICF compound nucleus  $^{147}\text{Ba}$  occurs, leading to the population of excited states in  $^{144}\text{Ba}$  and  $^{145}\text{Ba}$ , respectively, up to an angular momentum of about  $8 - 10\hbar$  with sufficient cross sections and thus sufficient  $\gamma$ -ray yields for a RDDS experiment.

## 1.1 Incomplete fusion after $^7\text{Li}$ breakup

It has been observed that measured complete fusion (CF) cross sections in reactions with weakly bound nuclei, e.g.,  $^7\text{Li}$ , above but nearby the Coulomb barrier are considerably suppressed as compared to different model approaches (see, e.g., [Cla05, Par16]). Therefore, detailed investigations of ICF reactions after  $^7\text{Li}$  breakup at near-barrier energies were performed in the past. These confirm that due to the low separation energy of weakly-bound  $^7\text{Li}$  direct breakups prior to reaching the barrier play a significant role for the total reaction cross section besides complete fusion as pointed out, e.g., in [Shr13, Das10].

Different theoretical approaches are able to explain this observation (see, e.g., [Gau17]). Especially, the separation of  ${}^7\text{Li}$  into a triton ( $t$ ) and an  $\alpha$  particle is prominent due to the well known weakly bound  $\alpha + t$  structure with a low separation energy of  $S_{\alpha/t} = 2.47$  MeV and thus a large breakup probability. More strongly bound and less studied clusters of  ${}^7\text{Li}$  as  ${}^6\text{He} + p$  with  $S_{{}^6\text{He}/p} = 9.98$  MeV and  ${}^5\text{He} + d$  with  $S_{{}^5\text{He}/d} = 9.52$  MeV (see [Shr13]) are of minor importance due to the higher separation energies.

In addition, it was proven that this suppression of the CF cross section at above-barrier energies due to breakup of  ${}^7\text{Li}$  is almost independent of the target mass as pointed out in [Das10, Par10] for semi-heavy and heavy nuclei (see also [Luo13, Kal16]): for the reaction of  ${}^7\text{Li}$  with different isotopes at energies nearby the Coulomb barrier a nearly constant CF suppression factor of about 25% was determined, for example, for  ${}^7\text{Li}$  beam impinging on  ${}^{144}\text{Sm}$  [Rat13],  ${}^{152}\text{Sm}$  [Rat13],  ${}^{159}\text{Tb}$  [Gau17, Bro75, Rat09, Muk06],  ${}^{165}\text{Ho}$  [Rat09],  ${}^{197}\text{Au}$  [Pal14],  ${}^{198}\text{Pt}$  [Shr13] and  ${}^{209}\text{Bi}$  [Das04]. The most significant contribution to the ICF cross section results from the direct breakup of  ${}^7\text{Li}$  into  $t + \alpha$  due to the low separation energy.

Quantum mechanical calculations of individual CF and ICF cross sections that also take into account explicitly breakup continuum effects are very scarce in the literature as pointed out in [Par16, Par16a]. However, in this recent work [Par16] the existing experimental data on CF and ICF and total fusion (TF) cross sections have been reproduced simultaneously with continuum discretized coupled channel calculations proving that:

- (i) ICF accounts for the suppression of the CF cross section above the barrier.
- (ii) The ratio of the ICF cross section and that for TF is found to be constant for energies above the barrier consistent with experimental data and increases below the barrier.
- (iii) In the case of  ${}^7\text{Li}$  the cross section for ICF with the triton ( $t$ -ICF) is much larger than that of  $\alpha$ -ICF which is also evident from experimental data. This is especially relevant for our proposed experiment (and can be simply understood from the fact that the barrier for  $\alpha$  is higher than that for  $t$ ).

Regarding the latter topic it should be stressed that for ICF of  ${}^7\text{Li}$  with  ${}^{198}\text{Pt}$  the  $t$ -ICF cross section above the barrier was determined experimentally to be about an order of magnitude larger than that of  $\alpha$ -ICF independent on the beam energy [Shr13]. Similarly, this was concluded by Parkar *et al.* both for  ${}^{198}\text{Pt}$  and  ${}^{209}\text{Bi}$  [Par16]. Due to the general mass independence of the  ${}^7\text{Li}$  ICF/CF ratio it can be expected that a similar scenario is valid for the ICF of  ${}^{144}\text{Cs}$  and  ${}^7\text{Li}$  proposed here.

From a very recent investigation of ICF of a  ${}^7\text{Li}$  beam applied to  ${}^{93}\text{Nb}$  it turned out that also in this mass region ICF after  ${}^7\text{Li}$  breakup plays a significant role for the total cross section [Kum17]. Only for lighter nuclei it was found that direct breakup is unlikely to suppress the above-barrier fusion cross section. In [Kal16] it is stated that there is no direct breakup of  ${}^7\text{Li}$  in reactions with  ${}^{58}\text{Ni}$  and  ${}^{64}\text{Zn}$ . However, a systematic investigation for light nuclei is lacking so far.

To our knowledge, only one investigation of ICF in inverse kinematics using radioactive beams was performed. Bottoni *et al.* studied the  ${}^{98}\text{Rb} + {}^7\text{Li}$  reaction at the Coulomb barrier energy at REX-ISOLDE [Bot15]. Similar to the investigations of ICF with stable beams a large contribution of ICF to the TF cross section was found where the  $t$ -ICF results the most significant contribution with a cross section that is about a factor of five larger than that of the  $\alpha$ -ICF ( $\sigma_t = 26.6 \pm 0.7$  mb and  $\sigma_\alpha = 5.3 \pm 0.2$  mb, respectively).

Therefore, we can conclude that  $t$ -ICF is feasible for  $^{144}\text{Cs} + ^7\text{Li}$  to produce the compound nucleus  $^{147}\text{Ba}$  similar to preceding investigations of ICF with  $^7\text{Li}$  in different mass regions. Calculations with PACE4 result in a total cross section for  $^{144}\text{Cs}$  applied with an energy of 590 MeV (energy in the middle of the  $1.5 \text{ mg/cm}^2$  Li target layer corresponding to a center-of-mass energy of 26 MeV) to a  $^7\text{Li}$  target of about 650 mb. If we assume as a conservative approach that 20% of the total cross section results from ICF for a beam energy above the barrier this would yield a total ICF cross section of about 130 mb.

We chose a  $^{144}\text{Cs}$  beam energy of 680 MeV ( $= 4.7 \text{ MeV/u}$ ) so that, including the energy loss in the  $1 \text{ mg/cm}^2$  Au target fronting, the beam is slowed down to an energy slightly above the barrier of 530 MeV ( $= 3.7 \text{ MeV/u}$ ) behind the  $^7\text{Li}$  target layer. We should note that the beam energy was slightly increases as compared to proposal P-530 to optimize the population of excited states of interest in  $^{144,145}\text{Ba}$  (see section 1.2). Below the barrier also the ICF cross section drops rapidly (see, e.g., [Par16]).

It is not possible to draw a clear conclusion on the contribution from  $t$ -ICF to the TF cross section due to the overall complexity of the possible reaction channels including, e.g., the different breakup channels of  $^7\text{Li}$ . However, as  $t$ -ICF in all investigated cases was typically by far the strongest ICF channel we expect a similar situation for our proposed experiment. Thus the assumption that only 40% of the ICF cross section is  $t$ -ICF is realistic as a very conservative approach. This results in a  $t$ -ICF cross section of about 50 mb that is used for estimating the rates as given in our proposal P-530.

## 1.2 Reaction channels after $t$ -ICF

The main criticism of the INTC concerns the choice of the relevant experiment parameters as presented in proposal P-530, especially with respect to the neutron evaporation channel of the ICF compound  $^{147}\text{Ba}$ . We gave an excitation energy of  $^{147}\text{Ba}$  after ICF of  $^{144}\text{Cs}$  with a triton of 23.7 MeV. We agree with the INTC that this excitation energy would lead to a non negligible evaporation probability of more than 3 neutrons of the compound  $^{147}\text{Ba}$ , i.e., the 4n and 5n channels are expected to contribute significantly.

Within the Letter of Clarification we have done a careful evaluation of the available literature on this subject and calculations with the “Kinematics Calculator” included in the program package LISE++ [Lis17]. The latter include calculations for both the ICF reaction from our proposal and for some published experiments where reaction channels are analyzed and partly excitation energies of ICF compounds were determined experimentally.

The fact that the ICF compound excitation energies given in these publications and/or the observed ICF reaction channels agree with our results of calculations with the “Kinematics Calculator” of LISE++ supports the reliability of the latter. On the other hand, this means that the excitation energy of the ICF compound  $^{147}\text{Ba}$  of 23.7 MeV given in our proposal P-530 is far too high. This value was estimated from a PACE4 calculation assuming a fusion of the projectile  $^{144}\text{Cs}$  with a triton and neglecting the kinematics properties of the two fragments after the break up of  $^7\text{Li}$ .

In Table 1 we present the results of our new calculations and relate them both to data of already performed ICF reactions where such data are existing and to our proposed ICF reaction to  $^{147}\text{Ba}$  to prove that in the latter case the 2n and 3n channels are expected

Table 1: Details of the  $t$ -ICF reaction after  ${}^7\text{Li}$  breakup for the proposed experiment on  ${}^{144,145}\text{Ba}$  compared to the respective values for other experiments. Neutron separation energies  $S_{xn}$  were taken from [Wan12].  $E_{t\text{-ICF}}^{\text{calc/exp}}$  gives the excitation energy of the respective  $t$ -ICF compound nucleus given in the third line where “calc” denotes the results yielded by calculations with the “Kinematics Calculator” of LISE++ [Lis17] and “exp” the value determined from experimental data if available. “main channels” gives the evaporation channels that were mainly observed of the respective compound after ICF. Except for the neutron separation energies all other energies are given in MeV. \*Following [Cla05] for  ${}^{184}\text{Re}$  no  $\gamma$ -rays were observed. This may be caused by the low expected excitation energy.

	This proposal	[Bot15]	[Cla05]	[Shr13]	[Mod10]	P-419 <sup>1</sup>
Beam	${}^{144}\text{Cs}$	${}^{98}\text{Rb}$	${}^7\text{Li}$	${}^7\text{Li}$	${}^7\text{Li}$	${}^{132}\text{Sn}$
Target	${}^7\text{Li}$	${}^7\text{Li}$	${}^{184}\text{W}$	${}^{198}\text{Pt}$	${}^{186}\text{W}$	${}^7\text{Li}$
$t$ -ICF comp.	${}^{147}\text{Ba}$	${}^{101}\text{Sr}$	${}^{187}\text{Re}$	${}^{201}\text{Au}$	${}^{190}\text{Os}$	${}^{135}\text{Sb}$
					( $\alpha$ -ICF)	
$E_{t\text{-ICF}}^{\text{calc.}}$	17.7	17.1	21.5	22.6	25.7	10.9
$E_{t\text{-ICF}}^{\text{exp.}}$	–	19	–	–	–	–
$S_{2n}$ (keV)	8890	9190	13539	13449	13713	6910
$S_{3n}$ (keV)	12710	13347	21208	21033	21703	14268
$S_{4n}$ (keV)	18611	19262	27690	27545	27993	19883
main channels	2n,3n (expected)	2n,3n	2n	2n,3n	2n,3n	–
$E_{t\text{-ICF}}^{\text{calc.}} - S_{3n}$	${}^{144}\text{Ba}$ 5.0	${}^{98}\text{Sr}^{\text{calc}}$ 4.1	${}^{184}\text{Re}$ 0.3*	${}^{198}\text{Au}$ 1.6	${}^{187}\text{Os}$ 4.0	–
$E_{t\text{-ICF}}^{\text{calc.}} - S_{2n}$	${}^{145}\text{Ba}$ 8.8	${}^{98}\text{Sr}^{\text{exp.}}$ 6.0	${}^{185}\text{Re}$ 8.0	${}^{199}\text{Au}$ 9.2	${}^{188}\text{Os}$ 12	–

to be the strongest channels, i.e., a strong population of excited states in  ${}^{144,145}\text{Ba}$  can be achieved with the experimental parameters chosen. Due to the non-negligible energy loss of the  ${}^{144}\text{Cs}$  beam within the  $1.5\text{ mg/cm}^2$   ${}^7\text{Li}$  target layer the calculations for the proposed experiment were done with the  ${}^{144}\text{Cs}$  energy in the middle of this target layer (4.1 MeV/u). However, for estimating the maximum excitation energies for reactions at the front and back layer of the  ${}^7\text{Li}$  target these values were also calculated using the respective beam energies and concluded below.

- Reaction at beginning of  ${}^7\text{Li}$  target layer:  
Excitation energy  ${}^{147}\text{Ba}$ : 19.4 MeV  
 $E_{t\text{-ICF}}^{\text{calc.}} - S_{3n}$  ( ${}^{144}\text{Ba}$ ): 5.8 MeV,  
 $E_{t\text{-ICF}}^{\text{calc.}} - S_{2n}$  ( ${}^{145}\text{Ba}$ ): 9.6 MeV.
- Reaction at the end of  ${}^7\text{Li}$  target layer:  
Excitation energy  ${}^{147}\text{Ba}$ : 16.9 MeV  
 $E_{t\text{-ICF}}^{\text{calc.}} - S_{3n}$  ( ${}^{144}\text{Ba}$ ): 4.2 MeV,  
 $E_{t\text{-ICF}}^{\text{calc.}} - S_{2n}$  ( ${}^{145}\text{Ba}$ ): 8.0 MeV.

Therefore, from Table 1 we are able to confirm the experimental observations of the preceding investigations [Bot15, Cla05, Shr13, Mod10]: Using the calculated excitation

<sup>1</sup>Proposal P-419 was accepted by the INTC following the Minutes of the 48th meeting on Nov. 5 and 6, 2014. It was argued that “The technique involving triton transfer followed by neutron evaporation is new and potentially ground breaking in terms of its application with radioactive beams.”

energies of the  $t$ -ICF compound nuclei and the neutron separation energies the observation of the corresponding neutron evaporation channels can be clearly explained. Therefore, we can conclude that under the chosen experimental conditions in our proposal P-530 only the 2n and 3n evaporation channels of the  $t$ -ICF compound  $^{147}\text{Ba}$  are expected leading to the population of excited states in  $^{145}\text{Ba}$  and  $^{144}\text{Ba}$ . We should mention that we did the estimates in Table 1 using a slightly higher  $^{144}\text{Cs}$  beam energy of 4.7 MeV/u before the target corresponding to 4.5 MeV/u at the beginning of the  $^7\text{Li}$  layer as compared to our proposal P-530 to increase the population of higher excited states in  $^{144,145}\text{Ba}$  (see discussion below), but to still avoid the 4n evaporation channel from  $^{147}\text{Ba}$ . This does not change the parameters of the foreseen plunger experiment in any significant way. However, a precise estimate of the excitation energy of the residuals  $^{144,145}\text{Ba}$  is difficult due to the unknown kinetic energy of the evaporated neutrons. Calculations with the program codes CASCADE [Pue77] or PACE4 in principle allow for a determination of the kinetic energies of the neutrons and thus the expected excitation energy. But as CASCADE is based on data for nuclei close to the valley of stability it is not clear if results are still reliable for exotic nuclei. From our experience also PACE4 calculations are not always able to reproduce parameters of reactions to exotic nuclei in a sufficient way. Thus for getting an idea on the excitation energies of  $^{144,145}\text{Ba}$  we relate our proposed experiment to existing data for ICF reactions.

As is clear from Table 1 the parameters of our proposed experiment are quite similar to the one of [Bot15]. From an analysis of the experimental data the authors conclude that the 2n evaporation channel after  $t$ -ICF with  $^{98}\text{Rb}$  resulted in an excitation energy of the residue  $^{99}\text{Sr}$  of 6 MeV and an average angular momentum of  $^{99}\text{Sr}$  of  $16\hbar$ . For the 3n evaporation channel to  $^{98}\text{Sr}$  they deduced an excitation energy of 2 MeV and  $9.5\hbar$ . Thus similarly we expect to populate excited states in  $^{144}\text{Ba}$  (2n channel) and  $^{145}\text{Ba}$  (3n channel) up to about 2 MeV and 6 MeV, respectively, and also comparable angular momenta.

In the PhD thesis of V. Modamio [Mod10] a detailed analysis of the reaction  $^7\text{Li} + ^{186}\text{W}$ , especially the ICF channels, was done. After  $\alpha$ -ICF to the compound  $^{190}\text{Os}$   $\gamma$ -rays of  $^{188}\text{Os}$  (2n evaporation) and  $^{187}\text{Os}$  (3n) were strongly observed where even particle- $\gamma$  -  $\gamma$  coincidences were analyzed. Decays of excited states up to excitation energies of more than 5 MeV and angular momenta of  $20\hbar$  both with positive and negative parity were observed in  $^{188}\text{Os}$ . For  $^{187}\text{Os}$  excited states up to about 4 MeV and angular momenta of  $37/2\hbar$  also with positive and negative parity were observed.  $t$ -ICF with  $^{186}\text{W}$  leads to  $^{189}\text{Re}$  with an excitation energy of 25.5 MeV. After 2n evaporation  $^{187}\text{Re}$  is produced where states up to about 2.4 MeV were populated. [Mod10] gives no data on  $^{186}\text{Re}$  (3n evaporation), probably as a high level density is present in this odd-odd nucleus leading to only weak population of individual states.

Together with the data from Table 1 and the relation to the kinematics expected in our proposal this further supports that ICF is able to populate the states of interest in  $^{144,145}\text{Ba}$ .

### Angular momentum transfer in ICF

We aim to populate excited states in  $^{144}\text{Ba}$  up to the  $8_1^+$  to  $10_1^+$  and  $9_1^-$  to  $11_1^-$ - yrast states with excitation energies of  $E(10_1^+) = 2044.3$  keV and  $E(11_1^-) = 2279.1$  keV. An estimate of

the  $^{144}\text{Cs} + t$ -ICF reaction yielded a grazing angular momentum of  $11\hbar$ . [Cla05] observed excited states after  $^{184}\text{W} + ^7\text{Li}$  ICF fusion in  $^{188}\text{Os}$  up to the  $8_1^+$  state where the population intensity of yrast states drops about linear with the angular momentum. In the work by A. Jungclaus et al. [Jun02] a strong population of excited states with much higher angular momenta was detected in neutron-rich Dy isotopes after  $\alpha$ -ICF. For example, in  $^{160}\text{Dy}$  both yrast and non-yrast bands including a negative band with  $J^\pi$  up to  $28\hbar$  were observed. Therefore, from this experience and the arguments given in the last paragraph on the excitation energy of  $^{144,145}\text{Ba}$  after neutron evaporation it can be expected that  $t$ -ICF to  $^{144,145}\text{Ba}$  leads to the population of excited states with angular momenta of at least  $8 - 10\hbar$ .

### Choice of the $^7\text{Li}$ beam energy

A lower beam energy than that of  $E(^{144}\text{Cs}) = 4.5 \text{ MeV/u}$  that we chose in proposal P-530 would result in a  $^{144}\text{Cs}$  projectile energy below the Coulomb barrier before it passes completely through the  $^7\text{Li}$  target layer. Following, e.g., [Shr13, Par16] the ICF cross section drops rapidly below the barrier. Thus a lower beam energy would only decrease the total ICF cross section. On the other hand, for a higher beam energy of  $E(^{144}\text{Cs}) > 5 \text{ MeV/u}$  likely that the  $4n$  channel opens leading to the population of  $^{143}\text{Ba}$  and thus suppressing the  $2n$  and  $3n$  channels.

### Separation of the different ICF and CF channels

Regarding a contribution of CF we would like to stress that the  $\gamma$ -rays from evaporation residues do not represent an unwanted hindrance for the proposed experiment as the CF compound  $^{149}\text{Ce}$  is neutron rich and does not emit charged particles with sizable cross sections. From the CF compound nucleus  $^{149}\text{Ce}$  following PACE4 estimates only the  $1n$ ,  $2n$ , and  $3n$  channels to  $^{148}\text{Ce}$ ,  $^{147}\text{Ce}$ ,  $^{146}\text{Ce}$ , respectively, are expected to contribute to the total cross section of about 650 mbarn by about 2%, 60% and 38%, respectively. Therefore, the  $^{144}\text{Cs} + t$  ICF channels to  $^{144,145}\text{Ba}$  can be clearly separated from the CF channels by triggering on the emitted charged particles, i.e., in our experiment on the  $\alpha$  particles from  $^7\text{Li}$  breakup. It should be stressed that the use of the existing combined CD + PAD detectors that are used as  $\Delta E - E$  telescopes and that are mounted in the MINIBALL chamber downstream from the plunger target and degrader, i.e., under forward angle, allow for a separation of the different charged particles ( $p$ ,  $t$ ,  $\alpha$ -particles) emitted from the ICF channels. This was proven in several experiments using ICF and in different mass regions (see, e.g., [Cla05, Bot15, Mod10]). In general, the measurement of the total energy of the emitted charged particles is already sufficient for the ICF channel separation as was proven in a test experiment by our group at the Cologne FN Tandem accelerator [Woe15] with a  $^7\text{Li}$  beam and using a simple Si detector array made out of solar cells. But in practice it is likely that there is background in the Si detector spectra from tails of the higher energy signals from the scattered radioactive beam and recoiling reaction products which cause need for a  $\Delta E - E$ -measurement. However, alternatively a  $16 \text{ mg/cm}^2$  Ta protection foil placed in front of the CD + PAD detectors can be used to stop both the scattered radioactive beam and recoiling reaction products and only lets light charged particles pass through with a low energy loss so that these can be still

separated. The further advantage of this protection foil is that there is no implantation of radioactive isotopes in the CD detector that would accumulate during the experiment.

## 2 Radiation safety

The ISOLDE TAC reported that long-lived  $^{142}\text{Ce}$  (in fact it is  $^{144}\text{Ce}$ ) may accumulate and cause maintenance issues during LS2. In addition, a question was asked regarding the possible need to re-zone the hall in the case of intense primary beams which may also cause problems in scheduling the experiment.

In the following we shortly address this questions. However, a further detailed analysis should be done with the local technical groups if the arguments listed below are not completely conclusive.

The relevant decay chain is  $^{144}\text{Cs} \rightarrow ^{144}\text{Ba} \rightarrow ^{144}\text{La} \rightarrow ^{144}\text{Ce} \rightarrow ^{144}\text{Pr} \rightarrow ^{144}\text{Nd}$  (stable).  $^{144}\text{Ce}$  has a long half-life of 289 days and, hence, also the decay of  $^{144}\text{Pr}$  is expected to be delayed. The Q-value of the  $\beta$ -decay of  $^{144}\text{Ce}$  is small (318 keV for decays into the ground state of  $^{144}\text{Pr}$ ) and, in addition,  $^{144}\text{Ce}$  decays predominantly into the ground state (76.5%) of  $^{144}\text{Pr}$ . Emitted  $\gamma$ -rays following the decay for the other 24% are low in energy (<135 keV). For the decay of  $^{144}\text{Pr}$  the Q-value is significantly larger (about 3 MeV) but, again, the decays populates predominately the ground state with a probability of 98%.

Regarding radiation safety during the experiment we would like to stress that recoiling electrons from the decay of  $^{144}\text{Ce}$  are irrelevant due to the small Q-value. Recoiling electrons from the  $\beta$ -decay of  $^{144}\text{Pr}$  are expected to have a maximum range of 3g/cm<sup>2</sup>. This means that they are completely stopped, e.g., in a 1 mm thick lead foil. Therefore we should be able to drastically reduce the dose rate using a corresponding outer shielding of the beamline with a lead foil if required. We are aware that there might be a significant amount of prompt radiation ( $\gamma$ -radiation and bremsstrahlung) during the experiment but this should only be a local issue.

To avoid long-time contaminations within the MINIBALL beamline we propose to use protecting foils backing the latter from inside, especially for the beam line downstream from MINIBALL and the beam dump, i.e., where scattered beam particles and reaction products may cause an accumulation of activity inside the setup. These foils can be easily removed after the experiment and stored safely. Thus contamination of this part of the beamline can be avoided.

## 3 Beam intensity

The TAC informed us that the 95% linac efficiency quoted in the proposal is too high. Typical values for 2017 are 70-75%.

A lowering of the achievable beam intensity by about 25% would mean that we will reduce the number of target–degrader distances from six to only five. As the long lifetime of the  $2_1^+$  state in  $^{144}\text{Ba}$  of  $\tau(2_1^+) = 1.02(3)$  ns is already known and all other lifetimes of interest are expected to be in the range of few ps up to several 10 ps we propose to skip the target distance of 10 mm that is mentioned in the proposal and only measure five distances between 10  $\mu\text{m}$  and 0.5 mm instead, i.e., distances in the sensitive range for the lifetimes



of interest. Each distance will then be measured for nearly 20 h instead of 16 h per distance as given in the proposal. This results in the same shift request of 15 shifts to complete the experiment (including the three shifts of a target-only measurement).

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