EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Direct measurement of superallowed β transitions with Lucrecia

September 26, 2023

V. Guadilla[1], J. Agramunt[2], A. Algora[2], M. Au[3], C. Bernerd[3], K. Chrysalidis[3], A. Fijałkowska[1], W. Gelletly[4], R. Heinke[3], A. Korgul[1], K. Miernik[1], E. Nácher[2], L. Nies[3], S.E.A. Orrigo[2], B. Rebeiro[5], S. Rothe[3], B. Rubio[2], W. Satuła[1], C. Schweiger[3], S. Stegemann[3], J.L. Tain[2], J.C. Thomas[5]

[1]*Faculty of Physics, University of Warsaw, 02-093 Warsaw, Poland*
[2]*Instituto de Física Corpuscular, CSIC-Universidad de Valencia, E-46071 Valencia, Spain*
[3]*ISOLDE, CERN, CH-1211 Geneva 23, Switzerland*
[4]*Department of Physics, University of Surrey, GU2 7XH, Guildford, UK*
[5]*GANIL, CEA/DRF-CNRS/IN2P3, Boulevard Henri Becquerel, Caen, France*

Spokesperson: Víctor Guadilla [vguadilla@fuw.edu.pl]
Contact person: Sebastian Rothe [Sebastian.Rothe@cern.ch] and
Simon Stegemann [simon.thomas.stegemann@cern.ch]

CERN-INTC-2023-057 / INTC-I-259
26/09/2023

Abstract: The aim of this Letter of Intent is to propose the use of the Lucrecia total absorption spectrometer for the direct determination of ground state to ground state superallowed β transitions. These superallowed branching ratios are employed for testing the unitarity of the Cabibbo-Kobayashi-Maskawa matrix, and they can be used to constrain models for isospin symmetry breaking corrections. Such branching ratios are usually indirectly obtained from γ-ray spectroscopy measurements, potentially impaired by Pandemonium effect for the nuclei we are considering. Cases for future proposals will be discussed and we will focus on the measurement of the yields, isobaric contaminants and release times of the two most challenging ones: ^{70gs}Br and ^{74}Rb.

Requested shifts: 10 shifts, (split into 1 run over 1 year)

1 Motivation

Superallowed $0^+ \to 0^+$ β transitions (pure Fermi) and superallowed mirror β transitions between analog $T = 1/2$ states in mirror nuclei (mixed of Fermi and Gamow-Teller) are known to be fruitful sources of information to test our understanding of the electroweak interaction. These transitions allow us to test the conservation of the vector weak current (CVC) and provide us with a precise value of the V_{ud} element of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [1]. For this the $\mathcal{F}t$ values are defined from corrected experimental nucleus-dependent ft values as follows:

$$\mathcal{F}t = ft(1 + \delta_R^{'})(1 + \delta_{NS} - \delta_C) \propto V_{ud}^{-2}(1 + \Delta_R^{V,A})^{-1} \quad (1)$$

where f is the statistical rate function that depends on the Q_{EC} transition energy and t is the partial half-life, determined from the total half-life, $T_{1/2}$, the β branching ratio, BR, and the electron-capture fraction, P_{EC}, as: $t = T_{1/2}(1 + P_{EC})/BR$. The terms δ_{NS} and $\delta_R^{'}$ are radiative corrections external to the weak interaction, $\Delta_R^{V,A}$ is an electroweak radiative correction and δ_C is the isospin-symmetry breaking (ISB) correction. While $\Delta_R^{V,A}$ is nucleus independent (only differs between Fermi and Gamow-Teller transitions) and $\delta_R^{'}$ depends on Z but not on nuclear structure, the isospin symmetry breaking correction is strongly dependent on nuclear structure details and δ_{NS} also requires detailed nuclear structure calculations. Note that if CVC is satisfied, the $\mathcal{F}t$ value for pure Fermi superallowed transitions is a nucleus-independent constant (for mirror transitions the Gamow-Teller/Fermi mixing ratio has to be accounted for in order to obtain an equivalent constant value).

Pure Fermi transitions have been systematically studied for the last 50 years with the most updated experimental data in order to confirm the CVC hypothesis with identical $\mathcal{F}t$ values within uncertainties for different transitions and evaluate V_{ud} (for the most recent survey see Ref. [2]). Some years ago, it was proposed to use also the superallowed mirror β transitions for an independent determination of V_{ud} [3]. The resulting matrix element using these sets of superallowed transitions can be used to test the unitarity of the CKM matrix: $V_{ud}^2 + V_{us}^2 + V_{ub}^2$=1, which is considered a stringent constraint on the search for new physics beyond the Standard Model. The most recent evaluation of the unitary condition shows a 2σ tension with the Standard Model [1].

There are two main limitations in the above-mention approach: 1) the restricted number of superallowed transitions included in the evaluation and 2) the significant role played by nuclear structure-dependent corrections, specially the ISB correction that is expected to range from ∼0.1% to ∼2%, depending on the nucleus. The first limitation is related to the lack of experimental data required to evaluate the ft values for some superallowed transitions and to the precision needed in order to include them for weak-interaction tests. Currently 15 pure Fermi transitions [2] and 8 mirror transitions [4] are considered. The second limitation is related to the model-dependent character of δ_C and δ_{NS}, and to the difficulties to experimentally constraint them [5]. In particular, different models are used to compute the ISB corrections: shell model calculations with Woods-Saxon potential [2], Hartree-Fock calculations [6], density functional theory [7, 8] and recent ab initio calculations [9] are some relevant examples. Very recently some experimental observables (nuclear weak radii and nuclear charge radii) were proposed to constraint the ISB corrections [10].

In this LoI we address the experimental determination of the branching ratios, BR, of superallowed transitions, needed for the computation of ft. The precise and accurate knowledge of BR is crucial to confront the two limitations mentioned before. On the one hand, some transitions are not included in the final evaluation for weak-interaction tests because of the lack or low quality of the BR value. On the other hand, different sets of ISB calculations could be tested more stringently against CVC and against CKM unitary thanks to new branching ratio values. In addition, there is a third limitation that concerns solely the currently adopted BR values. It is related to the fact that such branching ratios, associated with ground state to ground state β transitions, are determined from traditional γ-spectroscopy measurements with HPGe detectors, in which this branch is hindered because of the absence of γ-radiation emission. For this reason, BR is typically obtained indirectly, as the difference between the total number of decays and the number of decays feeding excited states in the daughter nucleus. As noted by Hardy and Towner [11], such procedure can introduce a bias due to the Pandemoium effect [12], associated with the limited efficiency of HPGe detectors and resulting in many undetected weak γ transitions from levels at high-excitation energies.

The impact of the Pandemonium effect in the branching ratio of superallowed transitions is expected to be particularly important in medium-heavy nuclei, where the superallowed branch may compete with numerous weak allowed branches populating excited states at higher excitation energies. In the case of pure Fermi transitions, as discussed by Hardy and Towner [11], this is associated with expected Gamow-Teller branches populating many available 1^+ states. Recent experimental works estimated the Gamow-Teller β intensity in the superallowed $0^+ \to 0^+$ decays of ^{62}Ga [13], ^{70gs}Br [14] and ^{74}Rb [15] by considering low-lying 2^+ states in the daughter nucleus as collector states for the de-excitation of the 1^+ states fed in the β decay. However, the fraction of the Gamow-Teller β intensity that do not de-excite through these collector states is expected to be significant [11], and the most recent and precise works in this region tried to estimate it by means of shell model calculations [13, 15].

A well consolidated spectroscopic tool to avoid the Pandemonium effect is the Total Absorption γ-ray Spectroscopy (TAGS) technique, which relies on the use of high-efficiency scintillation crystals to detect the full γ cascade released in the de-excitation of the levels populated in β decay [16, 17]. One of such detectors is Lucrecia at ISOLDE, consisting of a 38 cm diameter and 38 cm height cylindrical NaI(Tl) crystal. Lucrecia has been successfully operated at ISOLDE for the last 20 years [18] and recently updated with a new tape station system, already employed in four recent experiments in the last two years. One unique feature of the Lucrecia setup is the possibility to tag on x-rays thanks to a HPGe telescope and on β electrons/positrons thanks to an ancillary β plastic detector. This allows us to study independently the EC and β^+ branches, while an untagged TAGS measurement provides us with a combination of both.

In this LoI we propose to use of the TAGS technique for the measurement of superallowed transitions not only because it overcomes the Pandemonium effect, but also because it provides us with a direct determination of the ground state to ground state transition in a natural way, even though no associated γ rays are emitted. This is due to the penetration of the corresponding β electrons/positrons in the crystal, in addition to the detection of the two positron annihilation photons in the case of β^+ decays. The response function corresponding to the population of the ground state is fitted as part of the deconvolution process employed in the TAGS analysis, as shown in Figure 1 left for a β^- decay. In the case of β^+ decays, the sensitivity and the efficiency of Lucrecia for the ground state to ground state branch are enhanced due to the annihilation photons, as shown in Figure 1 right, where the efficiency for positrons for the same end-point energy is almost three times the efficiency for electrons. Recently we have succesfully revisited a complementary method, developed 30 years ago [20], to determine the β feeding to the ground state [19] based on counting β-γ coincidences between a total absorption spectrometer and an ancillary β detector. We have succesfully tested the performance of this method for β^+ decays with simulations of the decay of ^{62}Ga. The best precision achieved with TAGS for the ground state feeding determination is 0.5%, reported for the decay of ^{100}Tc [21] with both methods (deconvolution and β-γ counting). The uncertainty in the BR value with these methods primarily depends on the contaminants of the experimental spectrum, and the β-γ counting method was found to be slightly more precise [19].

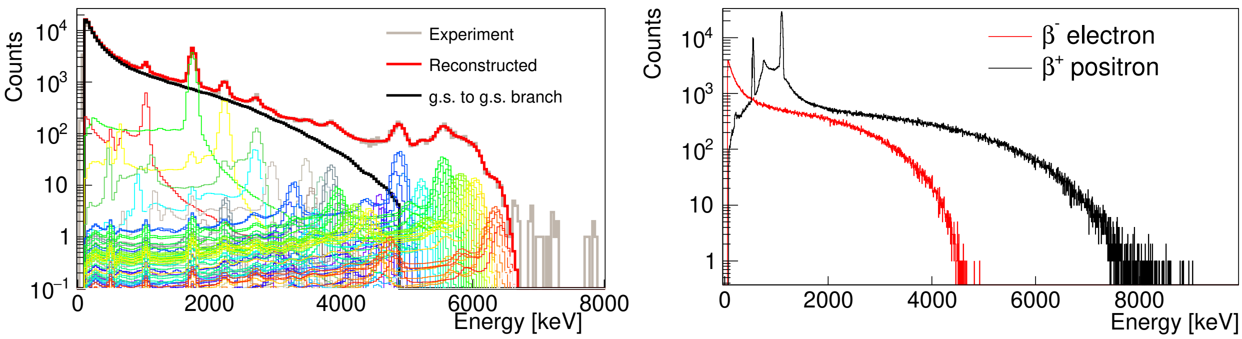

Figure 1: Example of TAGS deconvolution for the decay of ^{96gs}Y [22], where the ground state to ground state branch, amounting 96% of the β intensity, is highlighted (left panel). Comparison of electron and positron simulated responses of the Lucrecia spectrometer untagged for a β end-point energy of 8 MeV (right panel).

Nucleus	$T_{1/2}$ [ms]	Q_{EC} [keV]	BR [%]	P_{EC} [%]	Target	Ion source	Shifts
^{70gs}Br	78.42(51)	9970(170)	97.94(175) [14]	0.175	Nb foil	Surf-Neg	4
^{74}Rb	64.9(5)	10416.8(39)	99.543(31) [15]	0.194			
^{49}Mn	382(7)	7712.43(23)	91.6(20)	0.101	Nb foil	Surf-Ta	6
^{50gs}Mn	283.19(10)	7634.453(66)	99.9423(30)	0.107			
^{61}Ga	166(3)	9214(38)	94(1)	0.131	ZrO_2 felt	RILIS-W	-
^{62}Ga	116.12(23)	9181.07(54)	$99.8577^{+0.0023}_{-0.0029}$ [13]	0.137	ZrO_2 felt	RILIS-W	-

Table 1: Properties of the β decays discussed in the present LoI. Data from Refs. [2, 4], except other reference indicated. Details about the production of these nuclei at ISOLDE considered for this LoI are also included in the last three columns.

2 Physics cases

In the following we will discuss the selected superallowed transitions that we plan to study at ISOLDE. Some relevant decay parameters and production details are presented in Table 1.

• ^{70gs}**Br**: the pure Fermi transition dominating this decay is not included for electro-weak tests [2] because of the large uncertainties in the decay data. In addition, with the decay properties quoted in Table 1, the logft value obtained is higher than expected for pure Fermi superallowed transitions [23], evincing a tension between these decay data. The only experimental information concerning the BR value comes from Morales et al. [14] and it is quoted in Table 1. Shell model calculations predict 325 1^+ levels receiving 1.59% Gamow-Teller branching [11], while beyond-mean-field calculations [24] obtain an upper limit of 2% β strength distributed over many 0^+ states. However, in that experiment with the EURICA HPGe γ-ray array, all observed γ rays were attributed to the β decay of a 9^+ isomer lying at 2.29 MeV, with a much longer half-life of 2169(28) ms [14]. The missing β intensity was estimated by means of the 2_1^+ collector state, as mentioned before.

The possibility of constraining theoretical models for the ISB correction has become particularly interesting for this case in the light of the violation of isospin symmetry observed in the transition matrix elements of the $T = 1$ triplet ^{70}Kr-^{70}Br-^{70}Se [25]. A possible scenario with deformation has attracted a lot of attention and a large scale shell model analysis point to ^{70}Br as main responsible from the isospin symmetry deviations [26]. In addition, the determination of the full β strength for both 0^+ and 9^+ β-decaying states can also be useful to constraint theoretical models in a relevant region for the astrophysical rp process.

Note that there is also a long-standing problem with the Q_{EC} value of this decay that was already addressed in a previous proposal [27]. The value derived from a precise measurement of the mass of the ground state of ^{70}Br with Penning-trap spectroscopy [28] deviates from the systematics of Q_{EC} values for odd-odd nuclei (T_z=0) [29]. The discrepancy with the Penning-trap value was very recently reinforced by an isobaric multiplet mass equation (IMME) study [30] that exploited fresh mass measurements in the region [31]. The situation calls for a new precision measurement of the mass of the ground state of ^{70}Br, which establishes a synergy between this LoI and the ISOLTRAP active proposal [27] that plans to produce ^{70}Br with a ZrO or Nb-foil target with a hot VADIS ion source.

• ^{74}**Rb**: it is the heaviest superallowed Fermi transition included for electro-weak tests and the one with the largest associated errors [2], dominated by the Q_{EC} value and the nuclear-dependent δ_C correction, predicted to be the largest among all pure Fermi cases. The masses of ^{74}Rb and its daughter ^{74}Kr were already measured by ISOLTRAP almost 20 years ago [32, 33] but probably the Q_{EC} value could be now improved with the state-of-the art techniques of ISOLTRAP.

The BR value quoted in Table 1 has been indirectly determined at TRIUMF with an array of HPGe detectors in coincidence with the SCEPTAR β-taggig detector [15]. A detailed conversion-electron measurement was also carried out with the PACES Si(Li) detector [15]. A total observed β-intensity of 0.395(7)% associated with γ emission or conversion electrons was determined and authors estimated a 0.060(30)% missing intensity. This number needs to be verified with TAGS, given that shell model calculations predict hundreds of 1^+ states in the daughter nucleus and less than half of the γ cascades decaying through the 2^+ collector states [11].

• $^{49,50\mathrm{gs}}$**Mn**: only three 1^+ levels were clearly found to be fed in the β decay of $^{50\mathrm{gs}}$Mn into ^{50}Cr by Hagberg et al. [34], using samples mixed with the β-decaying isomer $^{50\mathrm{m}}$Mn (half-life of 1.75(3) min). In this study authors do not evaluate the BR of the superallowed $0^+ \rightarrow 0^+$ branch and no uncertainties are quoted for the Gamow-Teller decays to these 1^+ states. The BR value quoted in Table 1 has been derived by Hardy and Towner in their survey [2] and the corresponding uncertainty is most probably underestimated. In addition, there is a potential bias in the BR value due the possibility to populate extra states. Shell model calculations predict 16-35 1^+ states in ^{50}Cr [11]. In addition, possible non-analog feeding to other 0^+ states is conceivable. In a ^{52}Cr(p,t)^{50}Cr two-neutron pickup reaction experiment, two 0^+ states were identified in ^{50}Cr at 3895.0(5) and 4068.8(5) keV excitation energies [35]. Non-analog Fermi decay branches to those states still need to be checked experimentally. The study of this decay at ISOLDE could also benefit from the synergy between Lucrecia and IDS.

In the case of the superallowed mirror β transition from the $5/2^-$ ground state of ^{49}Mn, the BR quoted in Table 1 was indirectly obtained based on the deduced β intensities to two $7/2^-$ excited states in the daugher nucleus ^{49}Cr [36]. However, the level scheme of ^{49}Cr was later studied up to 4 MeV by means of the reaction ^{46}Ti(α,n)^{49}Cr [37], finding five extra levels that could be fed by allowed transitions in the β decay of ^{49}Mn, well reproduced by shell model calculations.

• ^{61,62}**Ga**: these two cases are included within the same scientific programme as potential cases for a future proposal but they will be briefly described here as their production does not need further tests: they are known to be well produced from a ZrO_2 target taking advantage of the Resonance Ionization Laser Ion Source (RILIS) [38, 39]. Note that it is the same target-source combination investigated for another TAGS proposal on Se isotopes [40].

The BR for the superallowed branch of ^{62}Ga, quoted in Table 1, was determined with great precision at TRIUMF with the GRIFFIN HPGe array and SCEPTAR [13]. In the case of the mixed Fermi/Gamow-Teller superallowed transition in the decay of ^{61}Ga, measured at ISOLDE [41] 20 years ago, there seems to be room for improving the BR value quoted in Table 1.

3 Production tests

The main goal of this LoI is to test the current feasibility of a TAGS measurement of the two most exotic cases discussed above: ^{70gs}Br and ^{74}Rb, already produced in the past at ISOLDE using 600 MeV protons from the Synchro-Cyclotron (SC) accelerator. For this, we plan to exploit the capabilities of the CERN-ISOLDE fast tape station [42] for yield determination, as well as the precision mass measurement potential of the ISOLTRAP experiment [43] for purity checks.

Apart from the production of bromide beams as a contamination in the form of $^{27}Al^{x}Br^{+}$ from a ZrO_2-felt target and a hot plasma ion source [44], bromide isotopes production was already studied at SC-ISOLDE in the 80s with a negative surface ionization source and a Nb-powder target [45]. A yield of 790 atoms/s for ^{70}Br was reported, but the associated half-life $T_{1/2}$=2.2(2) s suggests a dominance of the long-lived 9^{+} isomer. This calls for a new yield measurements that could be complementary to a coming production test of chloride isotopes planned at ISOLDE with a MK4 negative ion source and a Nb-foil target. We plan one shift for a yield measurement of ^{70}Br with the ISOLDE tape station plus one shift for final testing of the beams with Lucrecia. We propose two extra shifts, one for setting-up and one for purity checks and for the determination of the isomer/ground state ratio if the ISOLTRAP experiment [43] were ready to take negative beams, a development that is planned.

Neutron deficient rubidium isotopes production and release time was also studied in the past at SC-ISOLDE with a Nb-powder target and a positive Ta-surface ionization source [46]. The yield determined for ^{74}Rb was 1000 ions/μC. Considering that the yield was measured in the 90s with the SC accelerator at a different proton energy and with a Nb-powder target instead of Nb foils, it seems adequate to study the current production rate by new yield measurements.

Additionally, we plan to test the production of ^{49,50gs}Mn with the same target-ion source configuration as for ^{74}Rb, to combine these measurement campaigns. These isotopes were produced in the past with Nb-foil target and a W-surface ionization source [47]. However, the production with a Ta-surface ionization source is unknown. RILIS laser ionization [39] is, in both cases, needed. We plan to use ISOLTRAP for checking the ratio between the ground state of ^{50}Mn and the β-decaying isomer lying at 225 keV excitation energy.

We propose one shift with the ISOLDE tape station for a yield measurement of ^{74}Rb and ^{49,50gs}Mn from a Nb-foil target with Ta-surface ion source plus one extra shift for ISOLTRAP set-up and two shifts for purity checks and isomer-ratio measurements. We also plan two shifts for final testing of the beams with Lucrecia.

Summary of requested shifts: in total we request 10 shifts for testing the production of ^{70gs}Br, ^{74}Rb and ^{49,50gs}Mn, as presented in Table 1.

References

[1] A. Falkowski et al., Eur. Phys. J. A 59, 113 (2023)
[2] J. C. Hardy and I. S. Towner, Phys. Rev. C 102, 045501 (2020)
[3] O. Naviliat-Cuncic and N. Severijns, Phys. Rev. Lett. 102, 142302 (2009)
[4] N. Severijns et al., Phys. Rev. C 107, 015502 (2023)
[5] G. F. Grinyer et al. Nucl. Instrum. Methods A 622, 236 (2010)
[6] W.E. Ormand and B.A. Brown, Phys. Rev. Lett. 62, 866 (1989)
[7] W. Satuła et al., Phys. Rev. Lett. 106, 132502 (2011)
[8] M. Konieczka, P. Bączyk and W. Satuła, Phys. Rev. C 105, 065505 (2022)
[9] C.-Y. Seng and M. Gorchtein, arXiv:2304.03800 [nucl-th] (2023)
[10] C.-Y. Seng and M. Gorchtein, Phys. Lett. B 838, 137654 (2023)
[11] J. C. Hardy and I. S. Towner, Phys. Rev. Lett. 88, 252501 (2002)
[12] J. Hardy et al., Phys. Lett. B 71, 307 (1977)
[13] A. D. MacLean et al., Phys. Rev. C 102, 054325 (2020)
[14] A. I. Morales et al., Phys. Rev. C 95, 064327 (2017)
[15] R. Dunlop et al., Phys. Rev. C 88, 045501 (2013)
[16] B. Rubio et al., J. Phys. G: Nucl. Part. Phys. 31, S1477 (2005)
[17] A. Algora et al., Eur. Phys. J. A 57, 85 (2021)
[18] B. Rubio et al., J. Phys. G: Nucl. Part. Phys. 44, 084004 (2017)
[19] V. Guadilla et al., Phys. Rev. C 102, 064304 (2020)
[20] R. C. Greenwood, D. A. Struttmann, and K. D. Watts, Nucl. Instrum. Methods
[21] V. Guadilla et al., Phys. Rev. C 96, 014319 (2017)
[22] V. Guadilla et al., Phys. Rev. C 106, 014306 (2022)
[23] S. Turkat et al., Atom. Data Nucl. Data 152, 101584 (2023)
[24] A. Petrovici, Phys. Rev. C 97, 024313 (2018)
[25] K. Wimmer et al., Phys. Rev. Lett. 126, 072501 (2021)
[26] S. M. Lenzi, A. Poves and A. O. Macchiavelli, Phys. Rev. C 104, L031306 (2021)
[27] A. Algora, F. Wienholtz (spokespersons) et al., CERN-INTC-2017-047 (2017)
[28] J. Savory et al., Phys. Rev. Lett. 102, 132501 (2009)
[29] J. C. Hardy and I. S. Towner, Phys. Rev. C 91, 025501 (2015)
[30] W. J. Huang et al., Phys. Rev. C 108, 034301 (2023)
[31] M. Wang et al., Phys. Rev. Lett. 130, 192501 (2023)
[32] A. Kellerbauer et al., Nucl. Phys. A 746, 635c (2004)
[33] D. Rodríguez et al., Nucl. Phys. A 769, 1 (2006)
[34] E. Hagberg et al., Phys. Rev. Lett. 73, 396 (1994)
[35] K. G. Leach et al., Phys. Rev. C 94, 011304(R) (2016)
[36] J. Honkanen et al., Nucl. Phys. A 496, 462 (1989)
[37] F. Brandolini et al., Phys. Rev. C 73, 024313 (2006)
[38] U. Köster et al., Nucl. Instrum. Methods B 204, 303 (2003)
[39] V. Fedosseev et al., J. Phys. G: Nucl. Part. Phys. 44, 084006 (2017)
[40] E. Nácher, A. Algora, J.A. Briz (spokespersons) et al., CERN-INTC-2020-039 (2020)
[41] L. Weissman et al., Phys. Rev. C 65, 044321 (2002)
[42] S. Stegemann et al., Nucl. Instrum. Methods B 541, 169 (2023)
[43] M. Mukherjee et al., Eur. Phys. J. A 35, 1 (2008)
[44] U. Köster et al., Nucl. Instrum. Methods B 204, 303 (2003)
[45] B. Vosicki et al., Nucl. Instrum. Methods 186, 307 (1981)
[46] A. Jokinen et al., Z. Phys. A 355, 227 (1996)
[47] M. Oinonen et al., Hyperfine Interact. 127, 431 (2000)

DESCRIPTION OF THE PROPOSED EXPERIMENT

Please describe here below the main parts of your experimental set-up:

Part of the experiment	Design and manufacturing
If relevant, write here the name of the fixed installation you will be using [Name fixed/present ISOLDE installation: ISOLDE tape station, ISOLTRAP, Lucrecia TAS	☒ To be used without any modification ☐ To be modified
If relevant, describe here the name of the flexible/transported equipment you will bring to CERN from your Institute Standard electronic modules for Lucrecia	