EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Measurement of the decay scheme of ^{142}Cs

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Abstract: For a long time various experiments related to the yield of fission products have been indicating a singularity occurring at ^{142}Cs. These measurements suggest a renormalisation of the gamma-ray intensities in the decay scheme. A salient feature of this decay is the very low logft of 5.6 for the first-forbidden $0^- \rightarrow 0^+$ β transition to the ground state of the ^{142}Ba daughter. After renormalisation, it would become even lower, which seems unrealistic. However, a recent measurement with a total absorption spectrometer revealed a β-feeding pattern in disagreement with the decay scheme evaluated in Nuclear Data, though it does not solve the yield problem. In an attempt to solve the discrepancies we propose to study the decay of ^{142}Cs at the ISOLDE Decay Station to provide precise data on this nucleus including decay branching, feeding and the missing γ-ray intensity to address evaluated data for nuclear structure and also of significance for first-forbidden transition nuclei in reactor antineutrino anomaly studies.

Requested shifts: [10] shifts, (split into [1] run over [1] years)

1 History and Nuclear Data

According to evaluated data [1] the neutron-rich ^{142}Ba is a deformed nucleus with a $B(E2; 2^+ \to 0^+) = 33$ W.u. It is remarkable by the presence of a 1^- state at 1.326 MeV indicating octupole excitation (see Figure 1). Another unusual feature is logft $= 5.6$ for the first-forbidden beta transition from ^{142}Cs 0^- to the ^{142}Ba 0^+ ground state. Experiments in which ^{142}Cs was mass separated from other fission products have suggested to decrease the evaluated γ-ray intensities per decay. This, however, would further decrease the logft value, while the recommended lower limit is 5.9.
It is also noteworthy that there is no listed β feeding to the (3^-) and 4^+ states in ^{142}Ba, while the γ-ray intensity balance tells otherwise. It is problematic to match strong feedings to 0^+, 2^+, 1^- levels with weak but possible non-zero feeding to (3^-) and 4^+ final states.

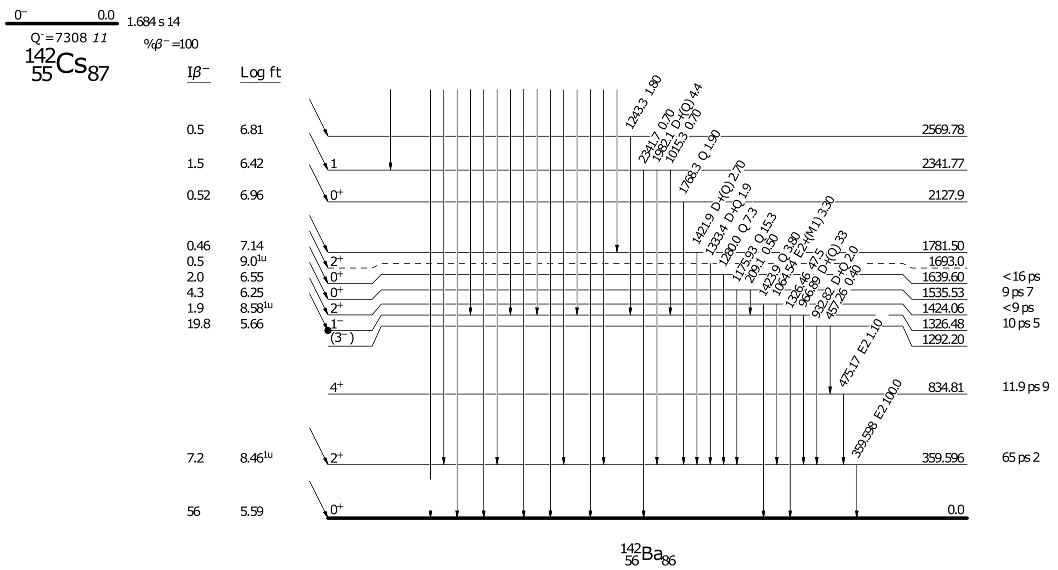

Figure 1: Decay scheme of ^{142}Cs adapted from ENSDF [1].

A singularity in the fission yield of ^{142}Cs has been observed about two decades ago using IGISOL systems, first by Kudo et al. in U(p,f) [2], then by Lhersonneau et al. in U(n,f) [3] where neutrons were produced by a deuteron beam as a first test of the SPIRAL2 production scheme. The yield measurements are relative but define the centroid and width of the distribution of isobars. The scale is fixed via an external measurement of the yield for the relevant mass chain [3, 4]. This can provide information on the reaction of the fission mechanism with the charge. Other measurements [5] studied systematically the output of the fission fragments from a Cf source and showed that there is a correlation with the ionisation potential of the element, with a particularly high efficiency for Cs.
Independently, in the context of the first version of SPES, the performance of a high-density uranium target designed at Gatchina (Russia) was tested [6]. The 1 GeV proton beam on target produced beams of Rb and Cs isotopes, together with minor contributions of their daughters Sr and Ba, using a surface-ionisation source. Since the cross sections of Cs isotopes and of their precursors had been measured at the GSI SHIP recoil separator in inverse kinematics by Bernas et al. [7], efficiencies of separation could be calculated. Decay losses during diffusion out of the UC_x grains and the randomwise effusion inside the

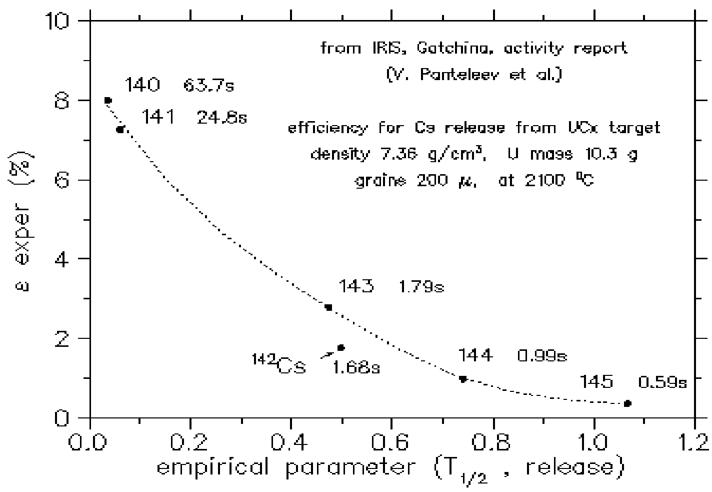

Figure 2: Efficiency of the separation of Cs isotopes at IRIS, Gatchina, deduced from decay spectroscopy, plotted versus a parameter containing the ratio of the nuclear half-life and an empirical time constant to represent the delayed release. Note that ^{142}Cs and ^{143}Cs have similar half-lives, 1.68 s and 1.79 s respectively, i.e. the efficiency should have been almost the same for both, but for ^{142}Cs it is clearly below the trend line.

target until the ionising surface makes the efficiency for a given element to vary smoothly with the nuclear half-life of the isotopes. A small discrepancy was systematically seen for the decay of ^{142}Cs, see Figure 2 taken from data in a report of a Gatchina-Legnaro-Ganil-Orsay collaboration sent to the European Union FP 7th program. A similar investigation was undertaken with the ISOLDE-SC yields [8] which conversely did not observe any strict deviation in yield.
A more recent measurement of the γ sum spectra using the Modular Total Absorption Spectrometer (MTAS) [9] confirmed the correction of a large discontinuity of the ^{92}Rb yield observed at IRIS by renormalisation of the γ-ray intensities listed in ENSDF [10]. The same MTAS paper moved the β feeding away from low-lying ^{142}Ba levels and indicated a larger feeding near 1.5 MeV and above 3.5 MeV than reported in ENSDF, see Figure 3. The small decrease of the β branch to the ground state from 56% to 44% makes the logft value slightly better to fit in systematics. However, this is the wrong direction to solve the yield problem.
The decay of ^{142}Cs is an important roleplayer in the field of reactor antineutrino anomalies [11] and the link to nuclear structure. Calculations of the antineutrino spectra from ^{235}U up to 4 MeV includes ^{142}Cs as one of the strongest contributors, and more recently the largest contribution at 6-7 MeV [12]. Moreover, it was recently shown that the understanding of first-forbidden transitions is crucial to the full understanding of the antineutrino spectra [13, 14]
The evaluated scheme of ^{142}Ba levels fed in the ^{142}Cs decay is not consistent with the experiments and calculations mentioned above. The missing γ-ray intensity has to be found. A full investigation would significantly contribute to the understanding of the structure of ^{142}Ba. Thus a new dedicated measurement is therefore essential.
The small decrease of the β branch to the ground state from 56% to 44% makes the logft value slightly better to fit in systematics.

2 Measurements

The measurement implies mass separation of ^{142}Cs from fission products at ISOLDE. A tape system is necessary to remove the activity of ^{142}Ba ($T_{1/2}$=10.6 m) which otherwise

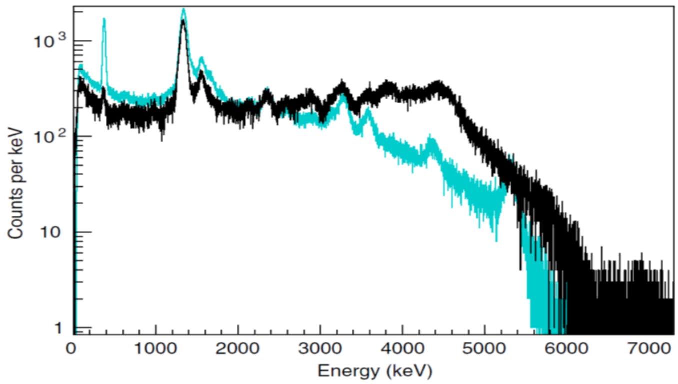

Figure 3: ^{142}Cs MTAS energy spectrum (black) compared to the simulated MTAS response to ^{142}Cs decay events based on the ENSDF data (cyan) [9]. The small decrease of the β branch to the ground state to 44% makes the logft value slightly better to fit in systematics however this may also include penetration of the Bremsstrahlung in the TAS. The experimental excess above 3.5 MeV is interpreted as the 'pandemonium'.

builds up during the experiment. The detectors should provide as near a 'complete' solid angle covering of the radiations, corresponding to at least two possible speculations where to find the missing decay flow, namely the so-called pandemonium and the large β feeding measured at the MTAS.

Pandemonium consists of the splitting of the γ-ray flow in many weak transitions that may remain undetected. The 7.3 MeV decay Q-value is very high and though transitions up to 5 MeV are reported in ENSDF, there still may be more of them. The fact that the 7.2% β feeding to the 2^+ state vanishes in the MTAS measurement could be the contribution arising from such γ-ray transitions ending at the 2^+ state. Figure 3 suggests that about 21% of the counts are missing in the calculated data above 3 MeV. Therefore, there might be other transitions (up to 14%) directly to the ground state, previously missed in direct spectroscopy due to their high energies. This implies that not only γ-γ coincidences, but also singles, should be recorded. Large volume Ge and $LaBr_3$ detectors in a modular system adding the escaped Compton scattered photons as they are available nowadays provide a better chance to identify such transitions than in the older measurements with small single crystals.

The second source of missing γ flow is based on the MTAS measurement proposing large β feeding near 1.5 MeV levels. A special effort should be made to find such feeding. It could be elucidated as γ rays, converted transitions, even $E0$ to the ground state. Gamma-ray detection should allow for the detection of low-energy transitions, down to the 32 keV K-X rays of Ba following internal electron conversion, and particle detection for the converted or $E0$ transitions. Yet, it is difficult to believe that all former studies have been missing γ rays associated with the extra β feeding near 1.5 MeV. If it is not an artefact of the unfolding of the MTAS data, it could indicate the existence of an isomer in ^{142}Cs. This isomer could have been present without the authors of decay works being aware of it. Long delays due to the finite release time and transport of activity before counting possibly precluded observation if the half-life is short.

The existence of an isomer is a delicate interplay of single proton and neutron levels. A spin larger than 4 and a half-life less than 1 second is a possibility, such as in ^{144}Cs, ^{146}Cs and ^{140}Cs [15, 16, 17]. In such a case, the levels fed with the extra β branches could have a rather high spin and be distinct from those observed in the decay of the 0^- ground state. Spin assignments possibly will have to be revised. It is noteworthy that such evidence for isomers is even lacking in literature for the laser spectroscopy measurements at ISOL facilities [18, 19] and almost certainly would have been measured.

The possibility of angular correlations is included. A half-life measurement by tagging the events with the time after the beam pulse is necessary to separate the decays if there is an isomer and if the half-lives are indeed enough different. Lifetimes of ^{142}Ba levels are of interest and values in the ps range are listed in ENSDF however with very small errors, but they may be sensitive to the way the measured levels are fed and consequently to changes in the decay scheme which we assume become evident. We note there is no lifetime listed for the (3^-) level, however it may be too short to be measured; clarification of this state (currently identified only through systematics) could be of interest for the octupole community.

3 Aims of measurements

- Measure angular correlations of γ rays using multi-gamma detector system
- Complete the scheme by looking for high energy γ-ray transitions
- Use good timing reference to get γ-ray energy versus time matrices to a) assign lifetime of nucleus (or contaminants) b) to identify possible isomer(s) c) establish the ground state beta branch using the decay of Ba for normalisation
- Electron spectroscopy of $E0$ transitions and investigation of excited 0^+ states and measure conversion coefficients of low lying $E2$ transitions in decay scheme
- Measurement of lifetime of low-lying transitions or from 0^+ to 2^+ decay lifetimes (for $E0$ strength measurements).

We would like to emphasise that both goals of the proposal (the measurement of high-energy gammas and the measurement of conversion electrons including possible missing transitions) are very ambitious for the clarification of the decay scheme. The investigation at high energies: (Q-value is 7.3 MeV) and discrepancies ensue above 4 MeV (see Figure 3) is a vital one, and the inclusion of the iThemba LABS African Lanthanum Bromide Array (ALBA) detectors play an important part of the measurement setup. In addition smaller $LaBr_3$:Ce detectors are available from the iThemba LABS fast-timing facility, together with associated 500 MHz Pixie-16 electronics compatible with the IDS data acquisition system.
The IDS conversion electron spectroscopy configuration, developed in 2018, employed a new SPEDE-like Si detector of 1 mm thickness together with 4 HPGe Clover detectors and a Si PAD in the forward direction for detecting β particles. The Cs ions will be implanted onto a mylar tape inside the IDS tape station. We will augment the station with four ALBA detectors forming a setup for γ-ray spectroscopy and angular distribution measurements. The absolute total efficiency of the HPGe detectors is 5.2% at E_γ=600 keV; 2.4% at E_γ=2000 keV when the add-back procedure is employed. For the ALBA $LaBr_3$:Ce detectors the efficiencies are 10% and 6% for the same energies. At even higher energies (4 MeV) the superior efficiency of the detector (3%) becomes invaluable for the experiment. Identical detectors have been used previously at ISOLDE in MINIBALL. There is a possibility of second measurement station (below primary implantation position) for lifetime measurements with 6-8 (2"x2") $LaBr_3$:Ce detectors.

4 Rate estimation

The yield from PSB is 2.6×10^5 atoms/μC. Discussing with Sebastian Rothe at the ISOLDE Users meeting in December 2019, this should provide a secondary beam of 2×10^5 atoms per second at the IDS taking into account a proton current of 2.0pμA and 50% transmission. The γ-ray solid angle for γ-ray detectors is estimated to be 62% at 75mm, and SPEDE at 12%. Taking an average of the γ-ray decay branching of 0.45%, typical α_{tot} conversion of 1×10^{-2}, typical photon total detection efficiencies (15% at 600 keV, 8% at 2 MeV) over the energy range (11%), we calculate the following:

Decay Mode	Transition Intensity (γ) % or ICC (e$^-$)	Detection/sec ($\times$ 10^{-2})	Hours per measurement
γ-decay	0.45	7080	0.1
γ-γ	0.45	6.69	54.0
Conversion electron	3.2×10^{-3}	4.91	73.5
electron-γ	3.2×10^{-3}	2.70	133.6

Summary of requested shifts:
We therefore request a total of ten shifts (9 spectroscopy, 1 for IDS optimisation) to complete the detailed spectroscopy of the decay scheme, using both γ rays and conversion electrons.

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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	☒ Existing	☒ Complemented with 4 ALBA detectors and second measurement station
[Part 1 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.

Additional hazards:

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure			
Vacuum	High Vacuum (10^{-6}mbar)		
Temperature	LN_2 temperature 77K		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	LN_2 1 bar 10l		
Electrical and electromagnetic			
Electricity	6kV, 5mA (HPGe, $LaBr_3$ supply)		
Static electricity			
Magnetic field			
Batteries	☐		

Capacitors	☐		
Ionizing radiation			
Target material [material]			
Beam particle type (e, p, ions, etc)	Ions: ^{142}Cs		
Beam intensity	2×10^5 s^{-1}		
Beam energy	60 keV		
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☒		
• Open source	☐		
• Sealed source	☒ [ISO standard]		
• Isotope	^{152}Eu, ^{137}Cs, ^{60}Co, ^{241}Am		
• Activity	1 - 10 kBq		
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)	Standard IDS Setup plus 4 ALBA detectors		
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): [make a rough estimate of the total power consumption of the additional equipment used in the experiment] 5kVA