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

Precise measurements of the β-decays of ^{9}Li and ^{8}He for reactor neutrino experiments

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Abstract: The decays ^{9}Li and ^{8}He produced by cosmic rays represent one of the largest irreducible backgrounds for reactor antineutrino experiments. The correct treatment of such decays are of therefore of large importance in developing methods for reducing this cosmogenic background. Existing data on the decay schemes of ^{9}Li and ^{8}He are insufficient for an adequate treatment of these backgrounds in current and planned reactor antineutrino experiments. This proposal suggest to provide this missing data at ISOLDE by measuring for the first time coincidences between neutrons and charged particles including β-particles.

Requested shifts: 18 shifts, (split into 2 runs of 10 and 8 shifts)

1 Motivation for studying the decays of ^{9}Li and ^{8}He

Experiments with nuclear reactors have played a major role in establishing our knowledge of the properties of neutrinos including the first direct demonstration of existence, and more recent experiments have helped with the elucidation of the properties of neutrino oscillations [1, 2]. Future reactor neutrino experiments will explore e.g. the neutrino mass hierarchy and search for sterile neutrinos and other new physics beyond the standard model.

Reactor neutrino experiments operate through the inverse β-decay (IBD) process $\bar{\nu}_e + p \rightarrow e^+ + n$,which is observed through the time correlation between the prompt signal from the positron and a later correlated signal from the capture of the neutron by either a proton or a gadolinium nucleus [1, 2], see Figure 1.

The energy of the prompt signal is related to the neutrino energy via $E_{\bar{\nu}_e} \simeq E_{prompt} + 0.78MeV + T_n$, with T_n being the kinetic energy of the recoil neutron. For IBD T_n is of the order of tens of keV and much smaller than $E_{\bar{\nu}_e}$, hence the neutrino energy can be determined by the prompt energy.

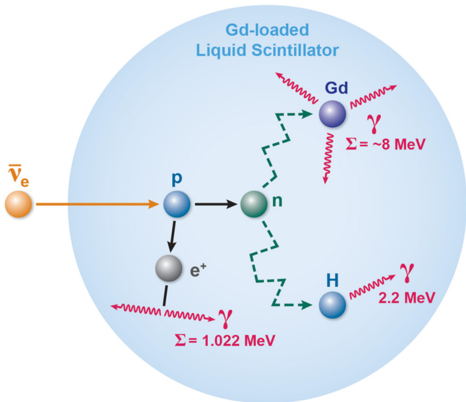

Figure 1: Principle of neutrino-detection in reactor neutrino experiments, figure from [2].

Radioactive isotopes produced by cosmic rays in the detector volume with an appreciable β-delayed neutron emission branch can mimic this IBD detection signal due to the simultaneous presence of an electron and a neutron. This provides a source of background with an energy spectrum determined by the decay scheme of the relevant radioactive isotopes. To understand this source of background in existing and future reactor neutrino experiments, and in particular understand how to discriminate it from true IBD events, Monte-Carlo simulations are used. These simulations are of course only as good as the physics put into them.

A recent paper by Jollet and Meregaglia [3] discusses how the most important sources of background of this type, ^{9}Li and ^{8}He, are implemented in the commonly used Monte-Carlo simulation tool Geant4. They evaluate the existing data on these two decays and provide updated radioactive decay datafiles for use in Geant4. Although their work provides a significant improvement over the previous treatment of these decays in Geant4, they conclude that the existing data is insufficient to provide an adequate description of this important source of background in reactor neutrino experiments, and that therefore

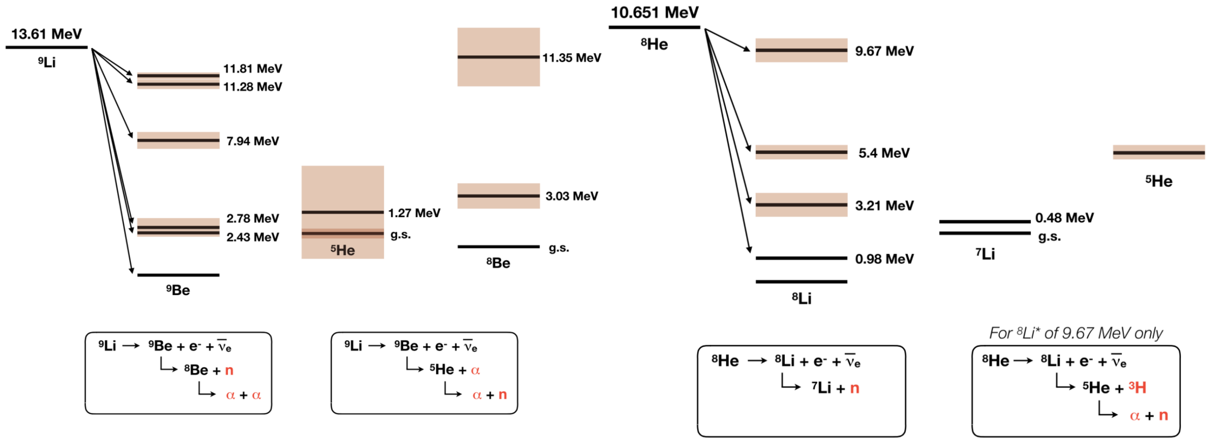

Figure 2: Decay schemes of ^{9}Li and ^{8}He from [3]. These decays are hard to clarify experimentally because states above the neutron threshold are short-lived and therefore have large widths. In addition, some of them breakup into final states of either $\alpha\alpha n$ (^{9}Li) or $\alpha t n$ (^{8}He) via intermediate resonances in ^{5}He and ^{8}Be some of which are also broad.

additional experiments aiming at a better determination of the energy levels and branching ratios of ^{9}Li and ^{8}He are required in order to further improve the simulation tools used by these experiments.

2 Limitations with existing ^{9}Li and ^{8}He decay data

Figure 2 shows the decay scheme of ^{9}Li from [3]. This decay scheme is hard to clarify experimentally because all excited states are above the neutron threshold at 1.5 MeV, and therefore they are short-lived resonances. In addition, they breakup into final states of $\alpha\alpha n$ via intermediate resonances in ^{5}He and ^{8}Be some of which are also broad. Hence, the spectra of α-particles and neutrons are featureless and hard to interpret in terms of a decay scheme. Three main studies of the decay of ^{9}Li are relevant:

- 1981, Langevin *et al.*: Suggests four resonances at 2.43MeV, 2.8MeV, 7.94MeV and 11.3MeV are populated in the decay [4].
- 1990, Nyman *et al.*: Also suggests four resonances, but finds no evidence for population of a resonance at 7.94MeV, and adds instead a resonance at 11.81MeV [5].
- 2005, Prezado *et al.*: Describes the data in terms of five resoances at 2.43MeV, 2.78MeV, 5.0MeV, 7.94MeV and 11.81MeV [6].

These experiments were not completed primarily with the aim of providing a description of the full decay scheme, but had more specific aims such as the decay mechanism of individual resonances, or the study of isospin mirror-symmetry in the population of individual resonances. The decay scheme in Figure 2 (left) shows the states included by Jollet and Meregaglia [3] in their updated radioactive decay datafile for use in Geant4. They do not justify their inclusion of the 11.3MeV state and their omission of the 5.0MeV state.

They point to a number of deficiencies with the existing data, most importantly, that uncertainties on the partial branchings ratios on the decay modes of the resonances are either very large or completely missing. This makes it impossible to calculate with known uncertainty the shape of the background in the reactor neutrino data from the decay of ^{9}Li.

The situation is somewhat similar for ^{8}He. Figure 2 (right) shows the decay scheme as implemented in the updated radioactive data file for Geant4 by Jollet and Meregaglia [3]. In this case there are two main experiments providing the existing knowledge of this decay [7, 8]. Data exists also from three experiments where final results are not yet to be published [10, 11, 12] (not used by Jollet and Meregaglia).

In the decay of ^{8}He there is general agreement that four 1^{+} states are populated in the daughter ^{8}Li. Apart from the lowest of these states, they are all unbound towards neutron emission and therefore relevant for the induced reactor neutrino background. The highest energy state can also populate the α-triton-neutron continuum. The neutron spectra measured by [7] and the unpublished[12] do not agree.

Jollet and Meregaglia [3] conclude that the existing data in the case of ^{8}He also is insufficient to adequately asses the induced background in reactor neutrino experiments.

3 Proposed experimental setup at the IDS

The requirement of the experiment is to provide as complete as possible a picture of the decays of ^{9}Li and ^{8}He. Our aim is to measure transitions with branching ratios down to 1% with precision 1-3% (compared to uncertainties that are presently in the range 7-30%, or completely missing). The setup must allow for coincident detection of charged particles (including β particles) and neutrons, which no previous experiment has offered - including unpublished results for ^{8}He[10, 11, 12].

We will use the IDS setup with the ISOLDE beam stopped in a thin carbon foil surrounded by a compact setup of Double-Sided Silicon detectors. Each DSSD will have a solid angle of 10-15% of 4π.

Neutrons will be measured with the Vandle array. Vandle has 40% integrated intrinsic efficiency; the precise value changes a little depending on the neutron energy spectrum. In the decays considered here, neutrons with energies up 7 MeV are emitted. For the total detector efficiency we estimate an angular acceptance of 15% of 4π for a 26 bar array.

A thin plastic scintillator with solid angle 10-15% of 4π will provide the start for neutron energy measurement via time-of-flight with Vandle. Vandle will be supplemented by two ^{3}He spectrometers for low energy neutrons. Measuring the neutron spectrum with both ^{3}He spectrometers and with Vandle may help resolve the discrepancy between the spectra measured by [7] (used a ^{3}He spectrometer) and [12] (used Vandle). By using energy and momentum conservation we may determine the missing particle in events where only either a neutron and one charged particle or two charged particles are detected.

We will attempt to measure the β-spectra from ^{9}Li and ^{8}He with a stack of thick Si detectors backed by a LaBr scintillator. The β-spectra will serve as a cross check on the deduced decay schemes. Measurement of the β-energy in coincidence with other charged particles emitted in the decay provides a direct determination of the prompt

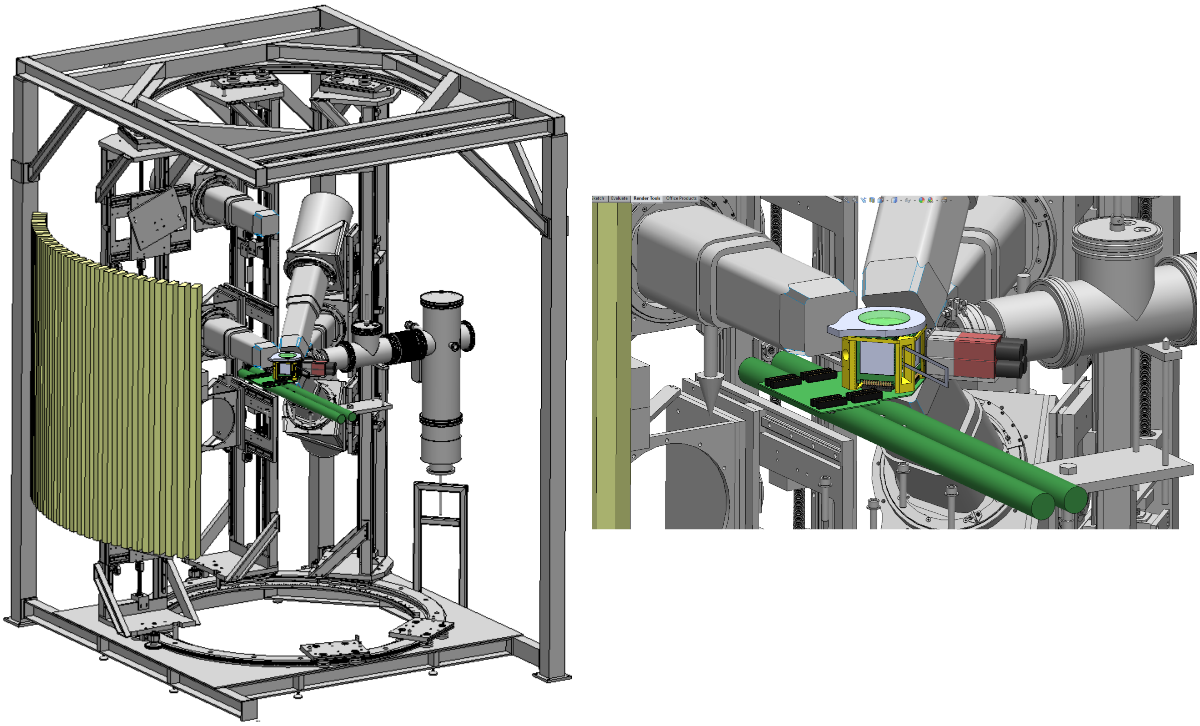

Figure 3: Setup at IDS. In the center an array of DSSDs. The green tubes are ^{3}He-neutron spectrometers, the yellow-green tubes are Vandle neutron detectors, and in grey and red is shown the LaBr detector for measurement of the β spectra.

signal required by the reactor neutrino experiments.
For the decay of ^{8}He, the IDS detectors will also measure the γ-rays from bound excited states in ^{8}Li and ^{7}Li.

4 Beamtime estimate

We base the beam time estimates on detection of four-fold coincidences between two charged particles in DSSDs, a neutron in Vandle and a β particle in a scintillator providing the start for TOF. The combined efficiency for such events is of order 6×10^{-5}.
We wish to measure transitions with branching ratios down to 1% with precision 1-3%, requiring 10^{3}-10^{4} events for such transitions. This sums up to a requirement for measuring in total 2-20×10^{9} decays. The yield of ^{8}He is of order 10^{4} ions/μC and that of ^{9}Li is in excess of 10^{6} ions/μC. For the latter we will only be able to accept of order 10^{5}ions/s in the setup. Thus we can produce of order 3×10^{8} ^{8}He per shift and up to 10 times more for ^{9}Li allowing for some losses for transmission to the setup.
Allowing for the fact that the decay of ^{9}Li is more complex than that of ^{8}He we allocate more beam time on ^{9}Li than on ^{8}He compared to what the estimates above suggest.
Summary of requested shifts: Based on this, we request 10 shifts of beam time of ^{8}He produced from a CaO target, and 8 shifts of beam time of ^{9}Li produced from a Ta target.

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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 Vandle array for neutrons and charged particle detector array based on DSSDs.

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 [Carbon-foil]	The C foils where the radioactive samples are implanted are very fragile. Should they break upon opening the setup, the pieces are so light that they would become airborne. Great care must be taken when opening the system and removing them. However, no long lived activities are expected.).		
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☒	Triple α source	
• Open source	☐		
• Sealed source	☒ [ISO standard]		
• Isotope	^{239}Pu, ^{244}Cm., ^{148}Gd		
• Activity	1 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)	[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): neglegible.