EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Study of multi-neutron emission in the β-decay of ^{11}Li

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Abstract

A new investigation of neutron emission in the β-decay of ^{11}Li is proposed. The principal goal of this study will be to directly measure for the first time for any system two β-delayed neutrons in coincidence and determine the energy and angular correlations. This will be possible owing to the use of liquid scintillator detectors, capable of discriminating between neutrons and ambient gamma and cosmic ray, coupled to a new digital electronics and acquisition system. In parallel, a considerably more refined picture of the single-neutron emission will be obtained.

Requested shifts: 19

Introduction

The β-decay of ^{11}Li has long been a subject of much experimental interest. This has arisen not only as a result of the halo character of ^{11}Li, but also owing to the very rich variety of decay modes it exhibits. In addition to delayed gamma-rays, single, two [Azu79] and three neutron [Azu80] emission is known to occur together with delayed deuteron, triton and alpha emission [Mad09,Mat09,Rab08,Mad08,Fyn04,Sar04,Til04]. This behaviour arises largely as a result of the very high Q_β (20.6 MeV) together with the very weakly bound nature of the daughter ^{11}Be (S_n=0.50 MeV).

Whilst the decay scheme of ^{11}Li involving gamma ray emission has been quite well established, that involving the emission of neutrons is much less well known. Indeed, despite a number of measurements being made using time-of-flight (TOF) arrays [Mor97, Aoi97,Hir05], there is still some uncertainty over the transitions present and the branching ratios. This is not surprising given the complexity of the decay scheme of ^{11}Li and the character of the associated delayed neutron spectrum. This is illustrated in Figure 1 which shows the TOF spectrum obtained from the most recent investigation (undertaken at ISAC-TRIUMF) of the β-n decay of ^{11}Li [Hir05]. The decay scheme derived using this data together with γ-ray coincidences is displayed in Figure 2. Clearly the neutron energy spectrum in the region of ~1 – 2 MeV is poorly described, whilst a number of the relatively weak unresolved transitions were included (based on possible neutron decays of known ^{11}Be states to ^{10}Be and denoted by the dashed lines in Figure 2) to improve the overall fit.

In the case of two-neutron emission very little is known beyond the total emission probability (P_{2n}=4.2(4) % [Bor97]). In terms of discrete transitions produced in sequential decay, Hirayama et al. [Hir05] have made a tentative identification of a decay from the 10.6 MeV state in ^{11}Be to the doublet at around 9.3 MeV in ^{10}Be (denoted "17" – E_n≈0.8 MeV) followed by a subsequent decay ("15" – E_n≈2.5 MeV) to the ^{9}Be$_{gs}$ as shown in Figure 2. Presumably the decay (also a tentative assignment) of the 8.82 MeV level in ^{11}Be to the 7.37 MeV level in ^{10}Be ("16"), could also result in a subsequent neutron decay to the ^{9}Be$_{gs}$, but the corresponding line (E_n~0.6 MeV) has not been seen, possibly owing to thresholds in the detection. Significant doubt, however, exists as to the veracity of these tentative assignments as, if correct, the two-neutron decay probability must be at least 10.1(1.5)% [Hir05], well in excess of the accepted value. It must be stressed that no measurement has yet been possible of the two-neutrons in coincidence, with inferences being made based on the single-neutron energy spectrum. As outlined below, the difficulty in directly detecting multiple neutrons in coincidence arises from the inability to discriminate the neutrons from the ambient gamma and cosmic rays.

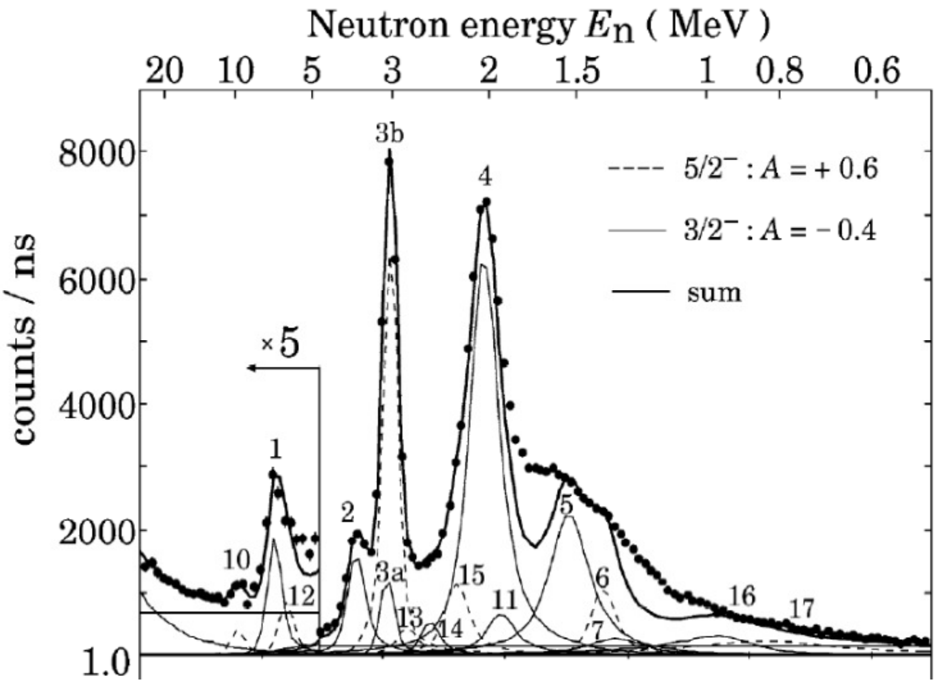

Figure 1: Neutron TOF spectrum for the β-decay of ^{11}Li [Hir05]. The various lines are labelled according to the placement in the decay scheme illustrated in Figure 2. (Note: the energy scale is non linear energy as the TOF is plotted).

By analogy with two-proton decay, two-neutron decay could proceed in some cases via simultaneous emission rather than a sequential process via a discrete intermediate level. In such direct decay the nature of the correlations between the two emitted neutrons is clearly of considerable interest and could serve as a probe of the configuration of the neutrons in the decaying state. In a very simplistic schematic picture competition between correlated (eg., di-neutron like) and uncorrelated decays could be imagined.

The direct detection of the two neutrons including a measurement of the energies and angles is very challenging and has so far proved impossible[1]. An attempt was made some years ago by members of the present collaboration using the TONNERRE plastic scintillator array (very similar in design to that used subsequently by Hirayama et al. [Hir05]). This measurement, employing a ^{11}Li beam supplied using the LISE3 separator, at

[1] Direct measurements of multi-neutron decay probabilities (P_{Xn}) rely on detectors in which the neutrons are moderated before detection and hence essentially all energy and angular information is lost.

GANIL proved conclusively that direct detection would only be possible provided that the neutrons could be discriminated from the ambient gamma and cosmic rays (μ). Indeed the rates at which these occurred in multiplicity two events recorded by TONNERRE far exceeded the expected number of true two neutron events and precluded any serious conclusions regarding two-neutron emission to be made (Figure 3).

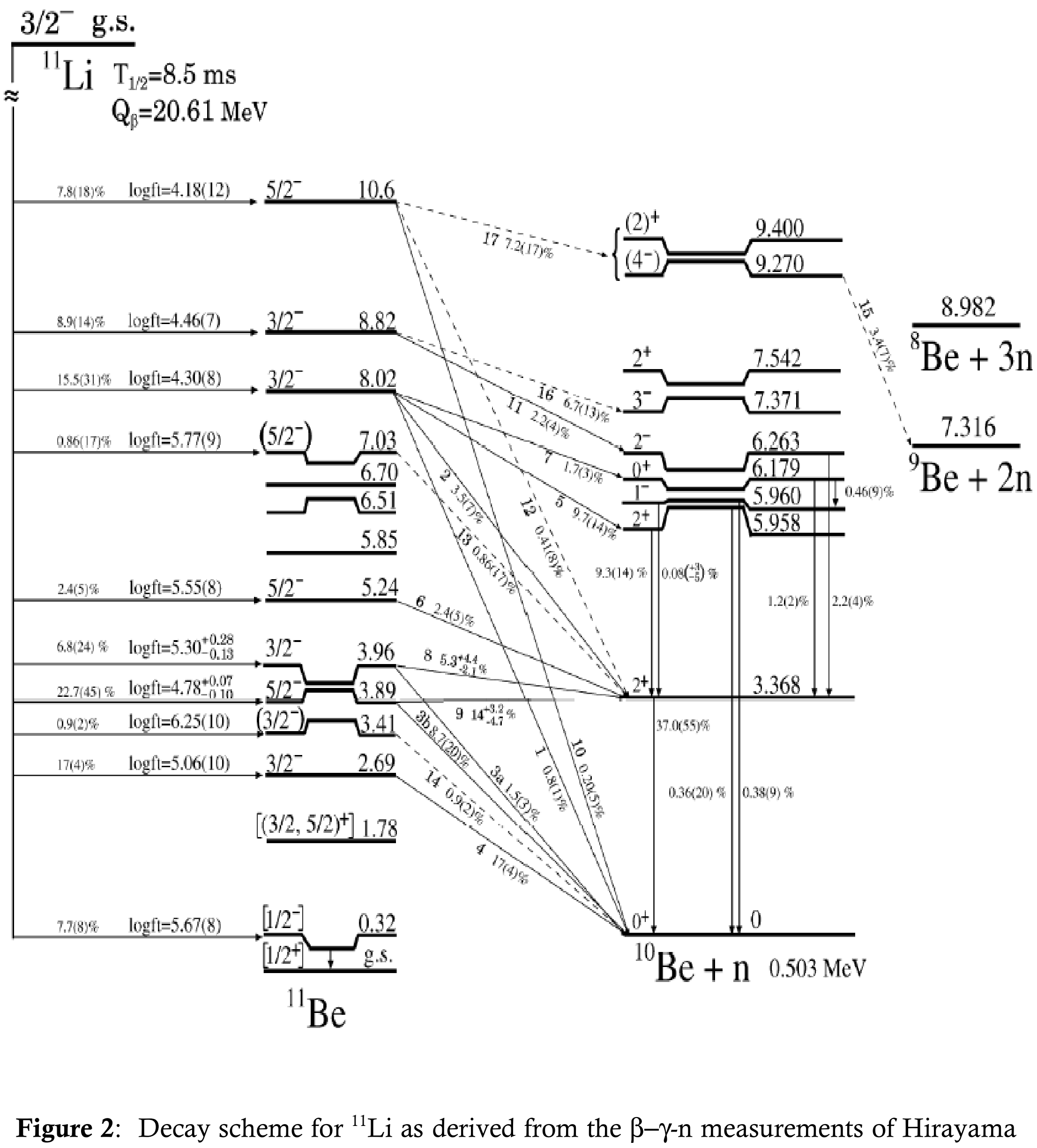

Figure 2: Decay scheme for ^{11}Li as derived from the β–γ-n measurements of Hirayama et al. [Hir05]

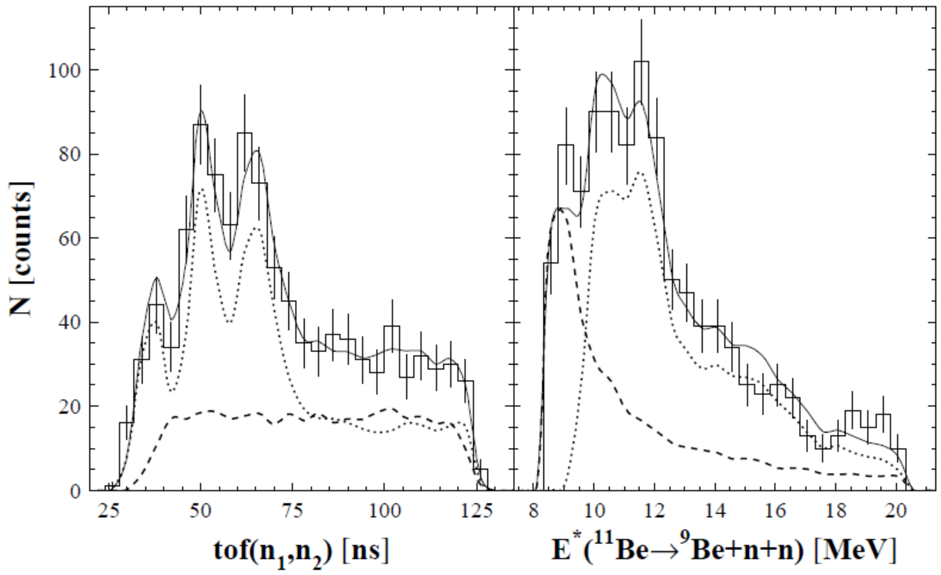

Figure 3: Neutron TOF and reconstructed ^{11}Be excitation energy spectra for multiplicity two events observed using the TONNERE array in the β-decay of ^{11}Li. The dotted and dashed curves represent the estimated contributions from n-γ/μ and μ–μ/γ–γ coincidence events respectively (the γ–γ type events being significantly reduced by removing those involving neighbouring detector modules).

Liquid scintillator detectors provide a means to discriminate, based on pulse-shape analysis techniques, neutrons from gamma and cosmic rays. In this context, the two groups leading the present proposal (LPC and CIEMAT) are developing new modular liquid scintillator arrays coupled to digital signal processing electronics for the detection of low-energy neutrons (E_n<10 MeV). It is proposed here to employ an early stage implementation (some 40 detectors) of the arrays to measure for the first time two decay neutrons in coincidence and determine the energy and angular correlations. As ^{11}Li is readily produced (~1000 pps at ISOLDE), has one of the highest presently known two-neutron emission probabilities (P_{2n}=4.2(4) %), and is of considerable physics interest, it has been selected as the object of a first study. In parallel to exploring the two-neutron emission and associated correlations, significant improvements will also be made to the understanding of the single-neutron emission from ^{11}Li by employing a section of the array at relatively large distances so as to significantly improve the energy resolution over earlier work. This feature may also prove useful[2] in allowing one of the transitions in the sequential decay to be tagged if it lies close in energy to another transition involved in two neutron decay.

[2] Provided that the limiting factor is not the intrinsic neutron width of the states.

Experiment

The experiment will employ a low energy ^{11}Li beam with an intensity of around 1000 pps [3]. The accumulation point, which will be a based on a tape system which can be used to remove any unwanted activity if necessary, will be surrounded by a plastic scintillator β-detector. The detection of a beta will provide the start for the neutron TOF measurement. An overall intrinsic timing resolution of 1.5 nsec or better is anticipated. At least one high efficiency Ge detector will be placed close to the implantation point to allow the coincident γ-rays to be recorded. Importantly the measurement of the feeding of the bound 320 keV state in ^{11}Be, the branching ratio of which is known, will serve as a reference point to facilitate the normalisation of the present measurements

The neutron detector modules[4] will comprise some 40 cylindrical cells of 20 cm diameter and 5 cm depth readout by large area PMT. The intrinsic detection efficiency for neutrons in the energy range of interest (~0.5-5 MeV) is expected to be, on average, around 40%. The neutron detectors will be arranged around the collection point at two different distances: 30 modules at 1.5 m and 10 modules at a distance of 3m. The former ("near" detectors) will be distributed on either side of the collection point, whilst the latter ("far" detectors) will be set downstream. The near detectors will provide for a measurement of the neutron-neutron coincidences with moderate energy resolution (70 at 1 MeV and 220 keV at 3 MeV), whilst the far detectors will provide for a higher resolution measurement of the single-neutron energy spectrum (35 keV at 1 MeV and 110 keV at 3 MeV) at the expense of a reduced solid angle coverage. Note that in the case of sequential neutron emission via discrete states, the neutron energy spectrum will be much simpler when the condition of the detection of two neutrons is required. Nevertheless, as some of the transitions involved in two neutron decay may lie relatively close together in energy, detection of one of the neutrons using the far detectors may be imposed, with the other being registered in the near detectors.

Unlike reaction experiments at high energies which produce very strong forward focussing of the neutrons, cross talk is not a significant issue in the detection of two neutrons from decay. First, for realistic detection thresholds (~100 keVee), no such events are expected to be generated below ~1.5 MeV incident neutron energy. Second, except for the case of strong di-neutron-like correlations, the two neutrons will be detected in widely separated detectors (cross talk beyond neighbouring detectors – ~0.5m separation – is estimated to be negligible). Third, any cross talk that does occur can be efficiently

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[3] This intensity at the collection point is based on experience from recent runs, such as that of Madurga et al. [Mad09] and [Kow11].

[4] Similar to those described in Ref. [Lau93]

eliminated using off line algorithms that we have developed and successfully employed at high energies [Mar00]. Indeed these procedures will be more efficient and easily implemented for the present study owing to the much increased flight times. At the time of writing of this proposal, preparations are being made for a run in late October at the neutron-beam facility at CEA-DIF of Bruyères-le-Châtel [CEA-DIF], using monoenergetic neutron beams in the energy range of interest for the present experiment, precise measurements of the characteristics of the neutron detectors, including the lineshape, intrinsic detection efficiency and the rates of cross talk. As a result, simulations that have been developed and compared to existing higher energy (E_n=14 and 37 MeV) data and that acquired with AmBe and Cf sources, will be further validated and, if necessary, fined tuned.

Beamtime Request

The limiting factor in the experiment is the probability of detecting two neutrons from the decay of ^{11}Li. To estimate the counting rates and beamtime request uncorrelated two neutron decay has been assumed (which also describes, to a good approximation, sequential decay). As noted earlier the average intrinsic neutron detection efficiency is ~40%, while the β-detection efficiency is expected to be ~80%[5]. Although the two neutron emission probability is 4%, some part of this strength may be unobservable with the present setup owing to the neutron detection threshold, which will be around 500 keV. We therefore assume that half the two neutron emission strength will be detectable (that is, an effective P_{2n} of 2%). Finally, based on recent experiments [Mad09,Kow11] an average ^{11}Li intensity at the collection point of 1000 pps is assumed.

For the near array of 30 detectors ($\Delta\Omega$=3.3% of 4π) a two neutron coincidence rate of 10 events/hour is expected. Thus, over 15 UT (5 days), a sample of some 1200 two neutron events will be recorded, which will be distributed over a number of different decay paths. In those cases where far detector ($\Delta\Omega$=0.28% of 4π) – near detector coincidences are required (see above), 1 event/hour is expected and thus some 120 in 15 shifts.

As described in the Introduction, significant improvements are expected in understanding the single-neutron decay. To illustrate this, it may be noted that for a 15 shift collection time, some 46000 counts will be accumulated using the near detector array (resolution similar to that of Hirayama et al. – Figure 2) for transitions with intensities of only 1%[6]. For the far detector array, with an expected energy resolution more than twice as good as that of Hirayama et al., some 3800 counts will accumulated for the same transition.

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[5] Essentially the geometrical acceptance of the plastic detector.
[6] An intensity comparable to the very weakest transitions, such as, for example, transition "14" of Figure 2.

It may also be noted that assuming a total photopeak efficiency of ~2% for the γ-ray detection, some 900 near array (80 far array) β–γ-n coincidences would be registered for a neutron line intensity of 1% feeding into a bound state in ^{10}Be that de-excites by emission of a single gamma-ray.

In addition to the data collection time with the ^{11}Li beam (**15 shifts**), **2 shifts** are requested for calibration purposes with a beam such as ^{49}K, which has a high single-neutron emission probability (P_n=86%), exhibits a number of well established β-n transitions in the range of interest and should be relatively easily produced from the same target-ion source combination (an intensity of only some 500 pps would be sufficient). A further **1 shift** is requested at the beginning of the run to tune the electronics and ensure that the setup is collecting data correctly, whilst **1 shift** is requested for the changeover from the ^{49}K test and calibration beam to ^{11}Li.

Summary of requested shifts:

The total beamtime request is **19 shifts** to be run concurrently in a single run. According to the ISOLDE data base, studies reported by Bergmann et al. [Ber02] and recent experience [Kow11], a Ta foil target – with intermediate thickness foils – and a Tungsten Surface Ionisation source should be employed to obtain reliably the necessary ^{11}Li intensities over the duration of the run. Whilst ^{49}K is not listed on the data base for the same target–ion-source combination, ^{48}K intensities orders of magnitude higher than the ^{49}K rate required here have been reported.

Finally, it is noted that the proposed experiment will form the central part of the thesis of M Senoville (LPC-Caen). As such, it is hoped that, if approved, the run will be scheduled before the winter shutdown of 2012.

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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 Choose an item.	Availability	Design and manufacturing
Detectors, supports, electronics etc supplied by collaboration partners.	☒ Existing	☒ To be used without any modification
Ge detector(s) might be requested from the MINIBALL array if available (to be negotiated at latter stage if proposal approved	☐ 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
	☐ 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 the experiment/equipment]*	*[Part 2 of the experiment/equipment]*	*[Part 3 of the 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)	11Li, 49K		
Beam intensity	of order 1000 pps		
Beam energy	Of order 60 keV		
Cooling liquids	Liquid N2 for Ge		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope	Std gamma-ray calibration sources + AmBe and/or Cf		
• Activity	Yet to be ascertained (depends on source availability at ISOLDE)		
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 (1-300MHz)			
Chemical			
Toxic	NE213 Liquid scintillator – approx 50 litres in total.		
Harmful	NE213		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	NE213		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	[chemical agent], [quantity]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the environment	[chemical agent], [quantity]		
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]		

3.2 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)*

Still uncertain at this point but likely to remain below 10 kW.