EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Pairing vibrations beyond $N = 82$

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Abstract: We propose to study pairing correlations in neutron-rich Xe isotopes. Theoretical predictions suggest an enhancement of the two-neutron transfer strength going to excited 0^+ states beyond $N = 82$. We will systematically compare the transfer cross sections to the ground and excited 0^+ states as a function of the projectile mass using beams of ^{134,136,138,140}Xe. The experiment will be performed at HIE-ISOLDE; 7 AMeV Xe beams will impinge on a radioactive tritium target and the ISS, operating at 2.5 T, will be used to measure and identify the proton recoils. The excitation energy will be reconstructed from the missing mass and the angular distributions will be extracted to identify 0^+ states. The goal of our experiment is to study neutron pairing correlations in neutron-rich Xe and establish if the predicted anomalous behavior of pair vibrations crossing the $N = 82$ magic number is indeed observed.

Requested shifts: 21 shifts, (3 Setup, 6 Stable- and 12 Radioactive-Xe's)
Installation: ISS

1 Scientific value

Pairing correlations play a crucial role in defining the properties of atomic nuclei. The evolution of these correlations in exotic nuclei is a subject which has received much attention in recent years, as new accelerator facilities are providing unique radioactive beams for experiments. Of special interest is the role of pairing in neutron-rich isotopes. In particular in the Sn isotopes, theoretical calculations based on Skyrme-Hartree-Fock mean field and continuum RPA predict a significant increase in the neutron pair-transfer strength to low-lying excited 0^+ states (pairing vibrations) for $N = 82 - 90$ nuclei. For very neutron-rich Sn nuclei with $A > 140$, a large increase in the pairing gap is expected, which results in an increased ground state to ground state pair-transfer strength [1, 2]. This behavior is attributed to the weakly bound $\nu 3p_{1/2}$ and $3p_{3/2}$ orbitals, which extend far beyond the nuclear surface. Currently, it is not possible to study Sn nuclei with $A > 140$, where the abrupt changes in the pairing transfer strength from excited states to the ground state occur. However, the region where pairing vibrations, characterized by strong transitions to excited 0^+ states in pair-transfer, dominate comes within reach of present accelerator facilities. As shown in Fig. 1 (a) the calculated pair-addition strength for the pair vibrational mode differs significantly between nuclei with $N > 82$ and below.

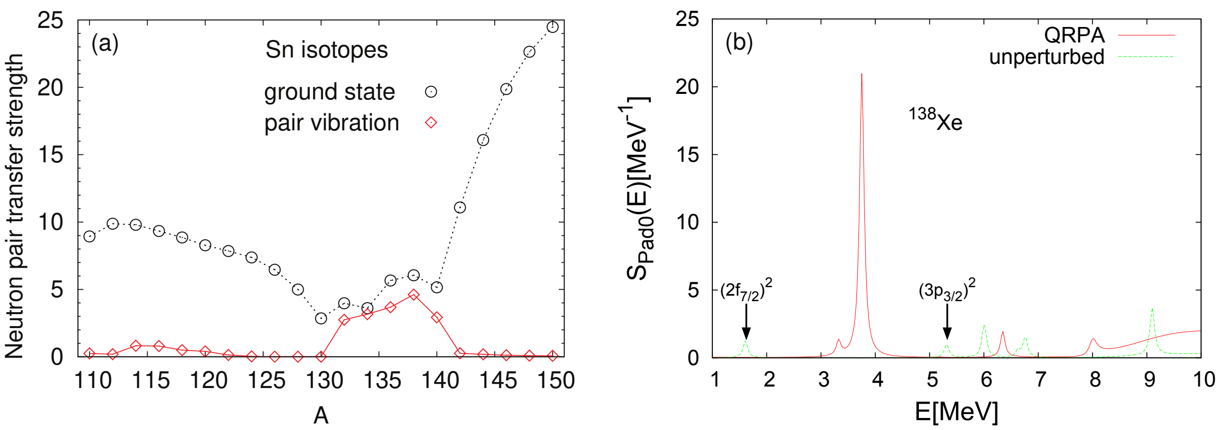

Figure 1: (a) Calculated pair-addition strength for the $A \to A+2$ ground state to ground state transition (black) and pair vibrational mode (excited 0_2^+ states, red) as a function of mass number A for the Sn isotopes. Between $A = 132$ and 140, the strength for the pair vibrational (PV) excitation becomes comparable to the one for the ground state. Figure adapted from Ref. [2]. (b) The pair-addition strength function $S_{\mathrm{Pad0}}(E)$ for ^{138}Xe $\to$ ^{140}Xe, calculated for the unperturbed neutron two-quasi-particle excitations (green) and in the quasi-particle random phase approximation (red). Figure adapted from Ref. [3].

The increase in the pair-transfer probability to the pairing vibration of $N > 82$ isotopes is almost independent of the form of the pairing parametrization used in the mean field calculations [1, 2]. The ideal reactions to study would be with exotic Sn beams impinging on a tritium target, but, at the moment, the intensity of Sn beams at HIE-ISOLDE is not sufficient for such a systematic measurement. However, as the change in transfer strength relates primarily to details of the neutron configurations, we expect a similar effect in the Xe isotopes to that predicted in the Sn isotopes. In fact, similar QRPA calculations for the ^{138}Xe have been performed showing that a very similar phenomenon is expected in Xe, despite the different proton number [3]. This is seen in Fig. 1 (b) where the pair-addition strength for ^{138}Xe is shown.

Motivated by these predictions, we propose an experiment that has the potential to look for a measurable signal of this intriguing difference. Two-neutron transfer reactions have been used extensively in the past to study pairing correlations and the superfluid nature of nuclei. Absolute and relative measurements of the $L = 0$ pair transfer cross-sections to the ground and excited 0^+ states along an isotopic chain give insights into the nature of neutron-neutron pairing . We propose to use beams of neutron-rich Xe isotopes, four protons above the Sn isotopes. We will systematically probe any change in the pair transfer strength to the pairing rotational ground states versus the pairing vibrational excited 0^+ states across $N = 82$ in the Xe isotopes. The transition densities $r^2 P_{\rm ad}(r)$ for ^{134}Sn and ^{138}Xe are compared in Fig. 2. These depend on the neutron Fermi energy and

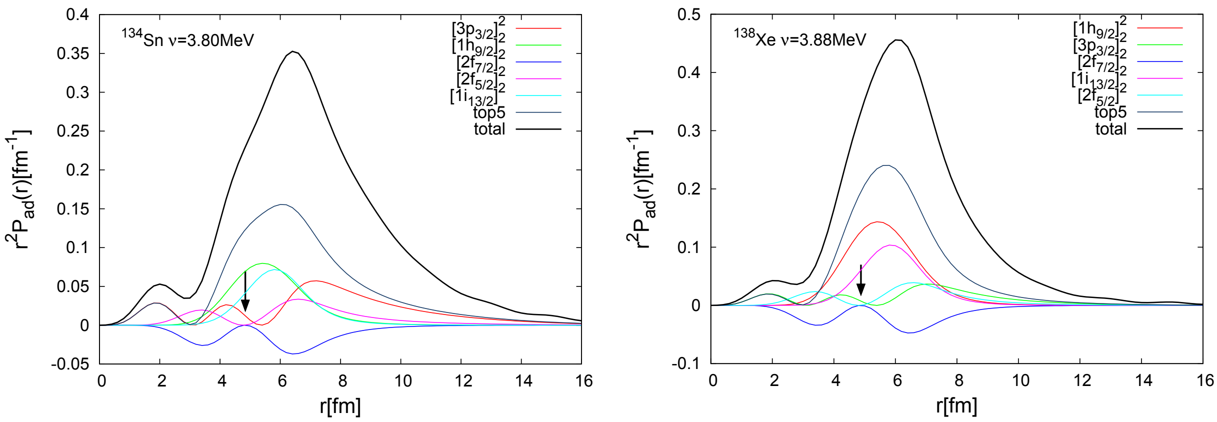

Figure 2: Neutron transition density in ^{134}Sn (a) and ^{138}Xe (b), for neutron two-quasi-particle excitations to the $2f_{7/2}$ and $3p_{3/2}$ states, compared to the transition density for the pair-vibrational mode. The arrow indicates the rms radius of the total nucleon density. Figure adapted from [3].

thus on the charge number Z, with the ^{138}Xe neutrons more bound compared to ^{134}Sn. The tail extending beyond 10 fm is less pronounced in ^{138}Xe, therefore a smaller cross section is expected. However, the effect is still much more enhanced with respect to stable xenon isotopes, and could be observed for the first time in the proposed experiment.

2 Experimental procedure

In order to study the nature of pairing excitation in the Xe isotopic chain we will use the (t, p) two-neutron transfer reaction in inverse kinematics to obtain the absolute and relative cross sections for the population of the ground and excited 0^+ states. We propose to systematically compare the transfer cross sections as a function of the projectile mass using beams of ^{134,136,138,140}Xe. This way, we will probe the anomalous behavior of the pair vibrations crossing the $N = 82$ magic number. In the Xe isotopes, the pairing vibration is predicted around 4 MeV [3], (see Fig. 1 (b)). Other 0^+ states of a different nature are predicted at 2 (^{138}Xe) and 1.5 MeV (^{140}Xe) [4].

2.1 Experimental setup

The experiment will be performed at HIE-ISOLDE using beams of stable ^{134,136}Xe as well as radioactive ^{138,140}Xe isotopes at a beam energy of 7 AMeV. The beam will impinge on a tritium loaded titanium foil (Ti thickness 0.5 mg/cm^2, atomic ratio t/Ti $\sim$ 1). Protons from the (t,p) two-neutron transfer reaction will be detected and identified by the Isolde Solenoid Spectrometer (ISS). ISS is ideally suited to measure the differential and integrated cross section for the $L=0$ (t,p) transfer channel, at forward (backward) 10-50° center-of-mass (160-100° laboratory) angles. Fig. 3 shows the reaction kinematics for the ^{138}Xe case. Besides the (t,p) two-neutron transfer reaction of interest, elastic scattering

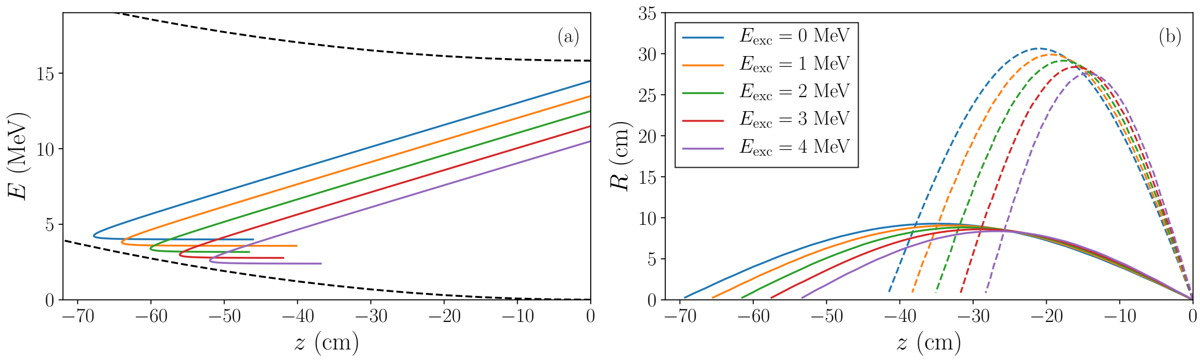

Figure 3: Reaction kinematics for a ^{138}Xe beam at 7 AMeV impinging on the tritium loaded titanium target. Panel (a) shows the energy of recoiling protons as a function of the position on the ISS silicon array. The reaction kinematics for different excitation energies in ^{140}Xe are indicated by different colors. Panel (b) shows the proton orbits for center-of-mass scattering angles 10° (solid lines) and 35° (dashed lines).

(t,t) will be observed by a forward detector. The latter is important to measure the luminosity, monitor the triton content of the target, and obtain the normalization of the cross section. A monitor detector will be placed at a fixed distance from the target to observed the forward scattering of the tritons. Based on our previous experience [5, 6, 7] the target is expected to contain some protons, so (p,p) elastic scattering will be measured as well, but these reactions can be distinguished based on the different energies of the light particles. For the cases of ^{134,136}Xe the reaction kinematics are very similar, only slightly shifted by the Q-value. The ^{138}Xe reaction has the smallest Q-value (675 keV) and therefore leads to the lowest proton energies. As shown in Fig. 3 (a), the ISS avoids the compression of the kinematic lines in the laboratory frame and provides an optimum setup for these studies. It should be mentioned that the (t,d) reactions will lead to some backward scattered deuterons, which will be identified by the cyclotron frequency. The accessible angular range in the center of mass system for the (t,d) reactions is very small, and therefore it is not clear how much information can be extracted from this additional data.

In Fig. 4 we show a full ISS (operating at 2.5 T) simulation of the ^{138}Xe(t,p) reaction for the population of two states. The excitation energy of the reaction ejectile ^{140}Xe can

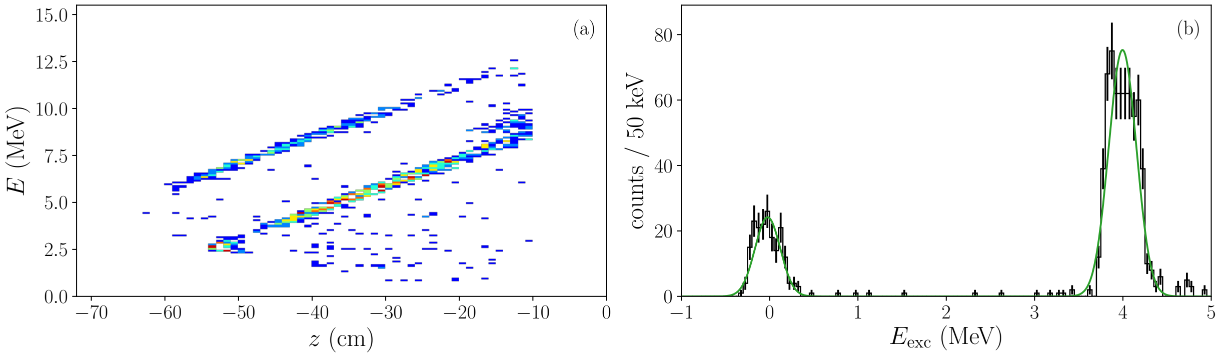

Figure 4: Simulation for the ^{138}Xe(t,p) reaction for the population of two states at 0 and 4 MeV excitation energy in ^{140}Xe. Panel (a) shows the proton kinetic energy versus the distance from the target. The detectors will be placed covering the solid angle from -10 cm. Panel (b) shows the excitation energy of ^{140}Xe reconstructed from the measured proton energies and positions. The resolution estimated this way is $\sigma = 130$ keV for the excitation energy.

be reconstructed with a resolution of $\sigma = 130$ keV. The dominant contribution being the energy loss of the beam in the target leading to the non-gaussian peak shape.

3 Beam-time estimates

Radioactive beams of Xe can be produced at ISOLDE from the PSB with a production rate of $\sim 1 \cdot 10^8$ ions/μC, using a standard UC_x target [8, 9] (see Table 1 for recent yield measurements). As a noble gas, Xe easily diffuses out of the target and will be ionized using the cold plasma ion source.

Beam	Yield /μC	Target material	Ion Source	Shifts
^{134}Xe	stable	none	EBIS	3
^{134}Xe	stable	none	EBIS	3
^{138}Xe	$1.6 \cdot 10^8$	UC_x	cold plasma	6
^{140}Xe	$0.8 \cdot 10^8$	UC_x	cold plasma	6

Table 1: Measured ISOLDE yields from [9]. Note that the numbers are smaller than the values given in the yield data base [8] as in the measurement from 2003 [10], the target was heated to 2200°C which should be avoided for an extended physics run.

Assuming 2 μA proton beam and 2% overall extraction/post-acceleration efficiency, in the following we consider a conservative beam intensity on target of $\sim 5 \cdot 10^6$ pps for the ^{138}Xe, and $\sim 3 \cdot 10^6$ pps for the ^{140}Xe(t,p) reactions. Past experience with Xe beams at HIE-ISOLDE, IS548, has shown that, due to the nobel gas nature, the only contaminants are decay products originating from the decay during the breeding of the beam

in the EBIS [11]. The relatively long β decay half-lives of ^{138,140}Xe, 14 min and 13.6 s, respectively, will result in smaller contamination than observed for ^{142}Xe during the IS548 experiment.
We will limit the current of stable Xe on the tritium target to 10^7 particles per second. This is still well below the current that was proven to be save in tests with deuterated titanium foils using stable Ar beams. Therefore, we account also for the different energy loss of the much heavier $Z = 54$ projectile. Furthermore, we will monitor the tritium content of the target during the experiment using the forward monitor detector.
The atomic ratio of 1:1 of tritium to titanium ions corresponds to an effective target thickness of 0.03 mg/cm^2 of tritium. The cross section for populating the pairing vibrational state is expected to be collectively enhanced over the single-particle cross section, as clearly seen in the QRPA results in Fig. 1 (b). DWBA calculations using standard global optical potentials [12, 13] for a single-step transfer to a pure $(3p_{3/2})^2$ configuration yield an integrated cross section of around 0.55 mb, and we use this as a conservative estimate for the cross section populating the pairing vibrational states in ^{140,142}Xe. Count rate estimates integrated over the range covered by the ISS array, based on our simulations, are shown in Table 2.

Beam	Intensity (pps)	reactions per h for 0.55 mb	Shifts 8 hour	Total reactions	Detected events
^{134}Xe	$1 \cdot 10^7$	119	3	2850	620
^{136}Xe	$1 \cdot 10^7$	119	3	2850	620
^{138}Xe	$5 \cdot 10^6$	59	6	2850	640
^{140}Xe	$3 \cdot 10^6$	36	6	1720	380

Table 2: Count rates estimates for the Xe(t,p) reactions proposed assuming a cross section of 0.55 mb for the pairing vibrational mode (PV). Total counts include the overall efficiency of ISS, in the CM (LAB) angular range 10-50° (160-100°), see Fig. 5 for the angles covered for the Xe(t,p) reactions. The solid angle coverage is slightly dependent on the Q-value.

For the radioactive ^{138,140}Xe beams we anticipate ≈ 500 counts for the pairing vibrational mode in the range of the ISS silicon detector array. This level of statistics corresponds to the simulations shown in Fig. 4. In previous (t,p) experiments with radioactive beams at ISOLDE [5], few hundred counts allowed for the identification of excited 0^+ states. In Fig. 5, we present the analysis of simulated data for the ^{138}Xe(t,p) reaction to two states with $(2f_{7/2})^2$ and $(3p_{3/2})^2$ configurations. The DWBA calculations predict 0.23 and 0.55 mb for these corresponding to ≈ 200 and 600 detected and identified events, taking into account the kinematics dependent acceptance of the ISS spectrometer. It can be seen that the level of statistics is sufficient to identify the characteristic shape of the differential cross section of 0^+ states. For the radioactive ^{138,140}Xe beams, we thus request 6 shifts for each isotope. Below $N = 82$ the cross section for excited states should be less. With one day of measurement, 3 shifts for each isotope, using stable ^{134}Xe and ^{136}Xe beams, we will be able to establish, if the predicted difference of pairing strength across the $N = 82$ magic number is indeed observed.
Tritium targets with an total activity of less than 10 GBq have been used in the past at Miniball/TREX and at the SEC. The implementation of a radioactive target for the ISS

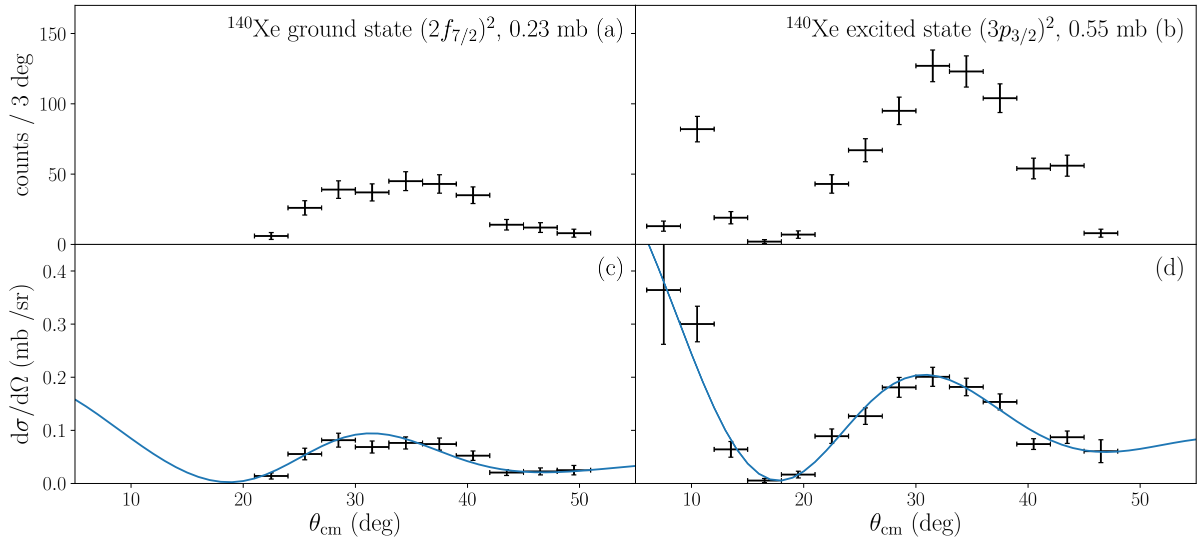

Figure 5: Simulation for the ^{138}Xe(t, p) reaction for the population of two states at 0 and 4 MeV in ^{140}Xe assuming $(2f_{7/2})^2$ and $(3p_{3/2})^2$ configurations, respectively. Panels (a) and (b) show the expected detected and identified proton counts for the two states. Panels (c) and (d) show the angular distributions corrected for efficiency and acceptance of the array, and compared with the DWBA calculations.

is under discussion with CERN RP and the ISS core members. Funding for a target is available. Anticipated delivery time is 9 month.
In total we request 21 shifts, 7 days, of beam time: six days of beam on target measurement (6 shifts stable, 12 shifts radioactive Xe beams) and 3 shifts for tuning, setup and debugging. This time is also required for switching the beams and tuning to the ISS target. While the stable beam part of the experiment could run any time without PSB protons, it would be advantageous, if the experiment were scheduled as one run to avoid systematic differences between the different beams. Furthermore, the operation of the tritium target requires substantial preparation of the setup at ISS.

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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
ISOLDE Solenoidal Spectrometer	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed ISS installation.

Additional hazards:

Hazards	
Thermodynamic and fluidic	
Pressure	
Vacuum	
Temperature	
Heat transfer	
Thermal properties of materials	
Cryogenic fluid	
Electrical and electromagnetic	
Electricity	
Static electricity	
Magnetic field	2.5 T
Batteries	
Capacitors	
Ionizing radiation	
Target material	Tritium doped Titanium
Beam particle type (e, p, ions, etc)	Xe
Beam intensity	10^7
Beam energy	7 AMeV
Cooling liquids	
Gases	
Calibration sources:	☒
• Open source	☒ existing α calibration source 4236RP
• Sealed source	☐
• Isotope	^{148}Gs, ^{239}Pu, ^{241}Am, ^{244}Cm
• Activity	1 kBq each

Use of activated material:	
• Description	☐
• Dose rate on contact and in 10 cm distance	
• Isotope	
• Activity	
Non-ionizing radiation	
Laser	
UV light	
Microwaves (300MHz-30 GHz)	
Radiofrequency (1-300 MHz)	
Chemical	
Toxic	
Harmful	
CMR (carcinogens, mutagens and substances toxic to reproduction)	
Corrosive	
Irritant	
Flammable	
Oxidizing	
Explosiveness	
Asphyxiant	
Dangerous for the environment	
Mechanical	
Physical impact or mechanical energy (moving parts)	
Mechanical properties (Sharp, rough, slippery)	
Vibration	
Vehicles and Means of Transport	
Noise	
Frequency	
Intensity	
Physical	
Confined spaces	
High workplaces	

Access to high workplaces	
Obstructions in passageways	
Manual handling	
Poor ergonomics	

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]: not applicable