EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Study of the neutron skin and soft dipole resonance in ^{8}He.

September 28, 2021

Y. Ayyad[1,2], B.P. Kay[3], J. Chen[3], A. Wuosmaa[4], G. Potel[5], H. Alvarez-Pol[1], F. Barranco[6], D. Bazin[2], R. Broglia[7,8], P. Butler[9],M. Caamaño[1], J. Casal[10] , B. Fernández-Domínguez[1], S.J. Freeman[11], L.P. Gaffney[9], C.R. Hoffman[3], M. Labiche[12], J. Lay[10], I. Lazarus[12], A. Moro[10] A. Munõz[1], B. Olaizola[13], R.D. Page[9] , R. Raabe[14], D. Regueira[1], D.K. Sharp[11], T. L. Tang[3], E. Vigezzi[15]

[1] *Instituto Galego de Física de Altas Enerxías, University of Santiago de Compostela, E-15782 Santiago de Compostela, Spain*
[2] *Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824, USA*
[3] *Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*
[4] *Department of Physics, University of Connecticut, Storrs, CT 06269, USA*
[5] *Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[6] *Departamento de Física Aplicada III, Escuela Superior de Ingenieros, Universidad de Sevilla, Camino de los Descubrimientos,Sevilla, Spain*
[7] *The Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Blegdamsvej 17, Denmark*
[8] *Dipartimento di Fisica, Università degli Studi Milano, Via Celoria 16, I-20133 Milano, Italy*
[9] *University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[10] *Departamento de Física Aplicada III, Escuela Superior de Ingenieros, Universidad de Sevilla, Camino de los Descubrimientos,Sevilla, Spain* [11] *School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK*
[12] *STFC Daresbury Laboratory, Daresbury, Warrington, WA4 4AD, UK*
[13] *CERN,CH-1211 Geneva, Switzerland*
[14] *KU Leuven, Instituut voor Kern- en Stralingsfysica, Celestijnenlaan 200d, 3001 Leuven, Belgium*
[15] *INFN Sezione di Milano, Via Celoria 16, I-20133 Milano, Italy*

Spokesperson: Y. Ayyad (ayyadlim@nscl.msu.edu)
Co-spokesperson: B.P. Kay (kay@anl.gov)
Co-spokesperson: J. Chen (jie.chen@anl.gov)
Contact person: B. Olaizola (bruno.olaizola@cern.ch)

1 Introduction

Most of the effort of modern nuclear physics is devoted to understanding how matter is structured at large N/Z imbalance. It is near and beyond the drip lines of the nuclear chart where the most fascinating and astonishing phenomena appear as a consequence of intricate microscopic interaction between the constituents of the nucleus. In fact, only a small amount of nucleons is needed to form systems with very different quantum properties. This is the case of the helium isotope chain where we can find numerous interesting features: ^{4}He is the most stable cluster found in almost every isotope under certain conditions and the ideal isotope to probe tensor correlations. ^{6}He and ^{8}He are Borromean halos with abnormal neutron separation energies and with no bound excited states. In particular, ^{8}He has the largest $N/Z = 3$ of all known bound isotopes. The halo features give rise to peculiar collective modes such as soft dipole or giant dipole resonances, very prominent in loosely bound light nuclei.

The halo nature of both, ^{6}He and ^{8}He was unveiled by means of interaction cross sections [1, 2], proton elastic [3, 4] and inelastic scattering [5], charge-exchange [6], break-up [7] and transfer reactions [8, 9]. From these experiments the *rms* matter radii R_m= 2.45±0.10 fm for ^{6}He and R_m= 2.53±0.08 fm for ^{8}He, from which the properties of the halo are inferred [10], was consistently deduced. Both *rms* are much larger than the one of ^{4}He (1.457), but very similar. This has been interpreted in terms of neutron skin vs halo [10]. The difference between them is subtle and hard to determine experimentally: the size of the neutron skin can be determined according to $r_{skin} = r_n^{rms} - r_p^{rms}$, the difference between the neutron and proton density distributions. On the other hand, halo nuclei feature a largely extended neutron density distribution. According to this picture, the difference of the density distributions between ^{6}He and ^{8}He has shown indicating the difference between a neutron skin and a neutron halo. The strongest evidence that supports the ^{8}He neutron skin was inferred from the analysis of the energy dependence of the reaction cross sections, from $40A$ to $120A$ MeV. Glauber calculations with density distributions consisting of a core plus a halo contributions were compared to the data [11]. The distributions were adjusted taking into account that the low energy cross section is more sensitive the the lower density part of the distribution. The ^{6}He needs a longer tail, compared to ^{8}He.

The neutron skin of ^{8}He was also deduced in an experiment that measured inelastic scattering and transfer reactions simultaneously, including ^{8}He(p,t) [12, 13]. Using the Coupled Reaction Channels (CRC) framework which includes direct transfer of two-neutrons, two-step transfer via ^{8}He(p, d)^{7}He reaction, and coupling between the 0^+ and 2^+ states in ^{6}He, the spectroscopic factors for 0^+ and 2^+ were found to be 1.0 and 0.014 respectively which shows a very small contribution of the ^{6}He(2^+) state in ^{8}He. The ^{8}He neutron skin was deduced (0.6 fm) considering that the g.s. is a mixture of $(1p_{3/2})^4$ and $(1p^{3/2})^2$ $(1p_{1/2})^2$. The conclusions of the CRC analysis in ^{8}He are quite different from the predictions from the cluster orbital shell model which suggests a ^{4}He+4n core, more on the 4 valence neutron halo idea [14]. The p(^{8}He, t) reaction was also studied investigated in a different with higher bombarding energy $61A$ MeV) [15]. The reaction was found to populate both the ground state and the 2^+ excited state of ^{6}He, contrary to what was inferred in the other (p,t) experiment. The inverse reaction, ^{8}He(t,p) was measured few years ago with the conclusion that the ratio of spectroscopic factors be the ^{6}He g.s. and 2^+ state does not depend on a strong configuration mixing as mentioned before, as this would imply a reduction on the $N = 6$ sub-shell closure [9], which is incompatible with the large separation energy of ^{8}He with respect to ^{6}He and the higher excitation energy of the 2^+. This stands as a conflicting situation that demands more precise measurements.

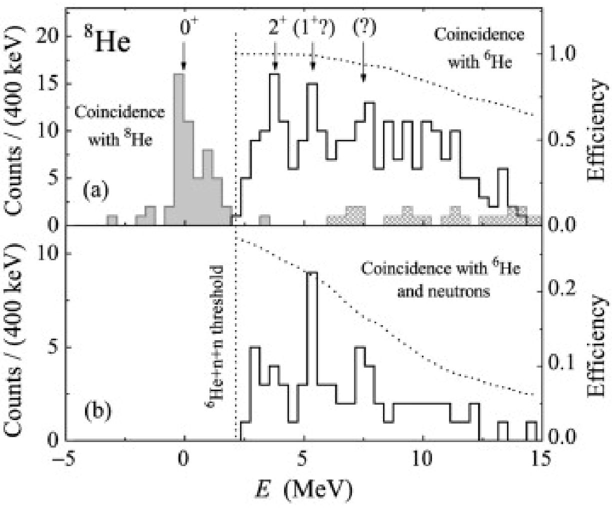

Figure 1: Excitation energy spectrum for the ^{6}He(t,p)^{8}He at $30A$ MeV. From Ref [9]

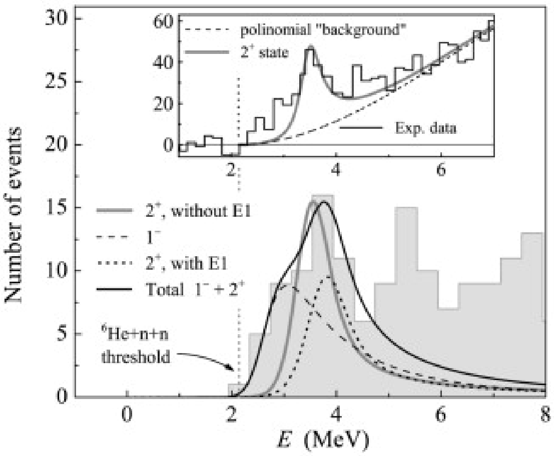

Figure 2: Spectrum of Fig 1 compared to the theoretical profile of the 2^+ state with and without a possible contribution of the 1^- continuum. The theoretical curves are convoluted with the experimental resolution. From Ref [9]

Generally speaking, the spectroscopic information about ^{8}He is rather poor. The value of the first excited state 2^+ varies from 2.7 to 3.6 MeV. The authors of Ref. [12] report another resonance above 5.4 MeV without any spin-parity assignment, but the excitation energy spectrum is not shown. The ^{6}He(t,p) spectrum, shown in Fig. 1 reported in Ref. [9] show very intriguing features. Two new states are reported: one at 5.5 MeV with 1^{+}, and an evidence of a state at around 7.5 MeV with unassigned spin-parity. However, the most interesting aspect is the possible existence of a soft dipole resonance (1^{-}) at around 3 MeV and evidenced by the presence of near ^{6}He+n+n threshold events [16] (see Fig. 2). This type of resonance is not unexpected in loosely bound nuclei. It was also observed in ^{11}Li using proton and deuteron resonant scattering [17, 18]. Although this type of resonance is interpreted as a vibration of the halo neutrons against the nucleons of the core moving in phase, it can be also viewed as a particle-particle state with two correlated halo neutrons acting as a nucleon Copper pair around an inert core [19, 20]. To investigate such low-energy dipole modes, two-neutron transfer reactions stands as one of the most promising tools. It is worth mentioning that no angular distributions were reported for this measurement.

In conclusion, the correct interpretation of the ^{8}He structure requires a new measurement with improved resolution and the determination of angular distributions to elucidate the proper spectroscopic factors and spin-parity of the states, mandatory to interpret a possible soft-dipole resonance in this nucleus.

2 Experimental details

We will use the ISS to analyze protons from the (t,p) reaction on ^{6}He at 10 MeV/u. We request a beam intensity of around 10^{6} pps, based on previous experimental data (4.70×10^{7} Yield/μC [21]) and confirmed by the beam development group [22]. The requested beam intensity, ideal to perform this experiment, is a conservative value lower than the previously achieved at the facility. It has been adopted to consider a possible reduction of possible contaminants from beam tuning and the ISS rate capability. We will use a titanium tritide target with an effective thickness of $\sim$45 μg/cm^{2} in $\sim$450 μg/cm^{2} of titanium. A similar target will be used for the IS695 experiment approved in the last INTC 67. The Si array, which surrounds the beam axis, is upstream of the target inside the solenoid. Simulations, shown in Fig. 3, suggest that an optimal set up will use a field of 2 T, with the Si array covering a distance of approximately $-450 < \Delta z < -100$ mm from the target. The information about the ^{8}He energy levels used in the simulation was obtained from the NNDC data base. Recoil detection will be achieved by means of annular silicon detectors in a telescope arrangement to determine energy loss and residual energy. These detectors impose an cut of $\theta_{\text{c.m.}} > 10^{\circ}$, due to the inner diameter of the annular detectors. We note that the reactions to unbound states will be clearly separated in the recoil detector. The recoil detector will be placed at 350 mm downstream of the target.

A very similar proof-of-principle experiment was performed at FRIB in August 2021 with a reaccelerated ^{10}Be beam. Figure 4 shows a very preliminary excitation energy spectrum of the ^{10}Be(t,p) obtained with SOLARIS [23] using a tritium loaded target with an effective tritium thickness of 20 μg/cm^{2}. The average beam intensity was around 10^{6} pps (instantaneous rate) during a running time of 7 days. The excitation energy

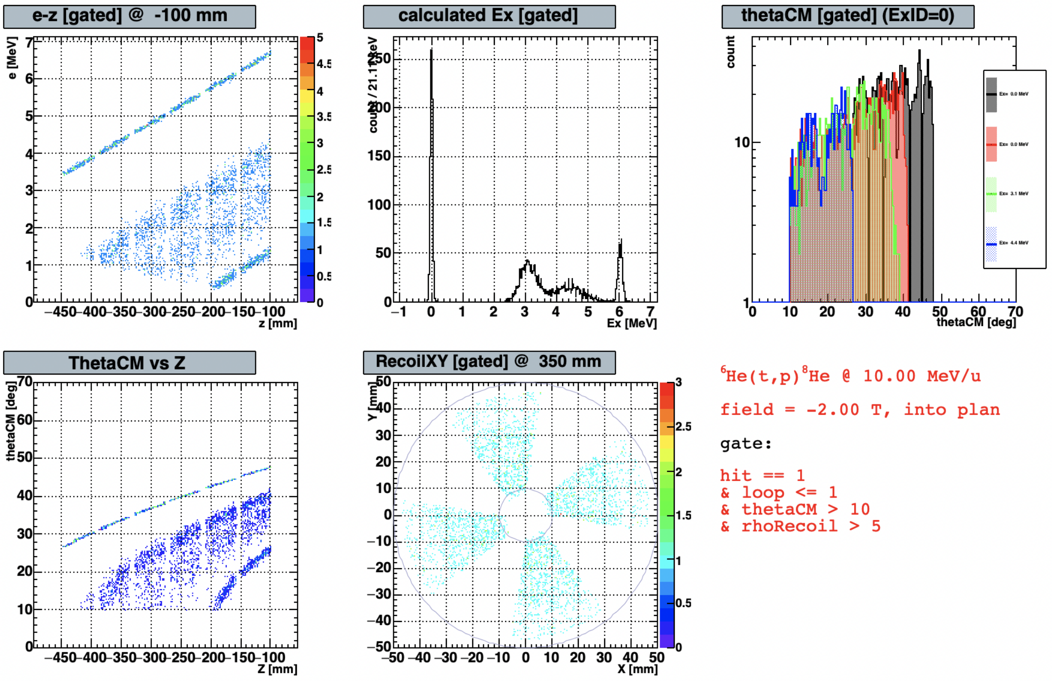

Figure 3: Simulation of the reaction taking into account the ISS geometry and the ^{8}He levels with their width. The excitation energy resolution was assumed to be 150 keV (FWHM), the typical values achieved in the ISS (HELIOS).

spectrum (preliminary resolution better than 200 keV FWHM) is almost background free thanks to the simultaneous detection of the heavy recoil and the excellent rejection of random coincidences using the timing between detectors. Taking into account that the time structure of the reaccelerated beam is similar to the ones produces in ISOLDE, it is clear that the ISS is an ideal instrument to perform (t, p) reactions with excellent resolution with titanium tritide targets.

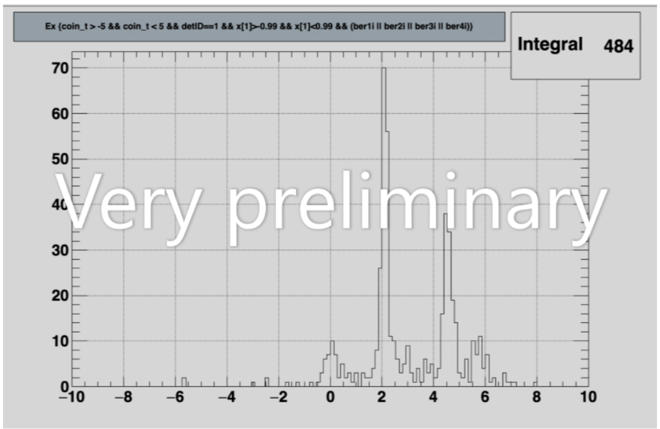

Figure 4: Excitation energy spectrum for the ^{10}Be(t,p)^{12}Be obtained with SOLARIS at 10*A* MeV [23]. The *X* axis referes to MeV. The ^{12}Be states can be clearly identified.

3 Beam time request and estimates

Rate estimates are based on the assumption of an angular coverage of $10° \lesssim \theta_{\text{c.m.}} \lesssim 45°$, with a 70% efficiency in the azimuthal angle and 94% efficiency in the theta angle. The differential cross section (Ref. [24]) for the ^{6}He(t,p)^{8}He(gs) has been determined taking into account a ^{8}He wave function with $(p_{3/2})^2$, $(p_{1/2})^2$, and $(s_{1/2})^2$ [25] and calculated optical potentials (see Fig. 5). To estimate the amount of beam time needed, we use a conservative differential cross section of 0.5 mb/sr averaged from the angular domain covered by the detector. These cross sections are consistent with the ones reported in Ref. [9], measured at higher beam energy ($25A$ MeV). In 7 days of measurement we will obtain, on average, around 70 counts per angular bin (5^o).

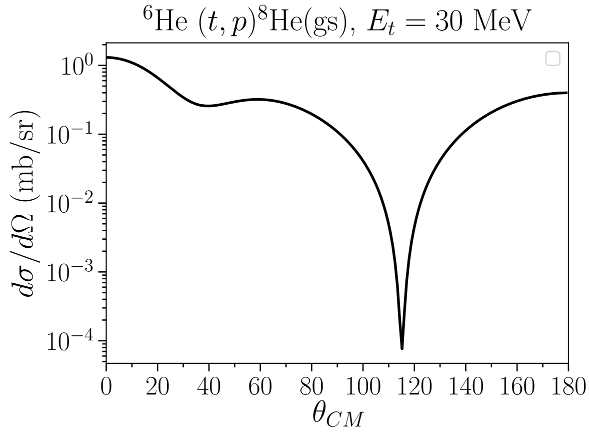

Figure 5: Calculated differential cross sections for ^{6}He(t,p)^{8}He(gs) using the formalism of Ref. [24].

Summary of requested shifts: We request 21 shifts of beam time to study the (t,p) reaction on ^{6}He at 10 MeV/u in inverse kinematics with the ISS to clarify the structure of ^{8}He and locate a plausible soft dipole resonance. In addition, recoil detection will be required to reject protons from reactions on titanium and other reaction channels as demonstrated in a previous experiment. The number of shifts requested is based on a beam of 1 MHz on target. We will use a titanium tritide target with an effective tritium thickness of 45g/cm^2. It is expected that Q-value resolution of 150 keV will be achieved. In addition, we request 3 shifts to perform the ^{4}He(t,p) reaction for calibration purposes. In total, we request **21 shifts of radioactive ^{6}He and 3 shift of stable ^{4}He** .

Appendix 1

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *The ISOLDE Solenoidal Spectrometer*

Part of the	Availability	Design and manufacturing
ISOLDE Solenoidal Spectrometer	☒ 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

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 T		
Batteries			
Capacitors			
Ionizing radiation			
Target material	Deuterated polyethylene (50-400 μg/cm^2)	Tritium tritide (45 μg/cm^2 tritium)	
Beam particle type	^{6}He	^{4}He	
Beam intensity	1×10^6	1×10^6	
Beam energy	10 MeV/u	10 MeV/u	
Cooling liquids			
Gases			
Calibration sources:	☒		
• Open source	☒ (α calibrations source 4236RP)		
• Sealed source			

• Isotope	^{148}Gd, ^{239}Pu, ^{241}Am, ^{244}Cm		
• Activity	1 kBq, 1 kBq, 1 kBq, 1 kBq = 4 kBq		
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): N/A

References

[1] I. Tanihata, H. Hamagaki, O. Hashimoto, S. Nagamiya, Y. Shida, N. Yoshikawa, O. Yamakawa, K. Sugimoto, T. Kobayashi, D.E. Greiner, N. Takahashi, and Y. Nojiri. Measurements of interaction cross sections and radii of he isotopes. *Physics Letters B*, 160(6):380–384, 1985.

[2] I. Tanihata, D. Hirata, T. Kobayashi, S. Shimoura, K. Sugimoto, and H. Toki. Revelation of thick neutron skins in nuclei. *Physics Letters B*, 289(3):261–266, 1992.

[3] G. D. Alkhazov, M. N. Andronenko, A. V. Dobrovolsky, P. Egelhof, G. E. Gavrilov, H. Geissel, H. Irnich, A. V. Khanzadeev, G. A. Korolev, A. A. Lobodenko, G. Münzenberg, M. Mutterer, S. R. Neumaier, F. Nickel, W. Schwab, D. M. Seliverstov, T. Suzuki, J. P. Theobald, N. A. Timofeev, A. A. Vorobyov, and V. I. Yatsoura. Nuclear matter distributions in ^{6}He and ^{8}He from small angle p-he scattering in inverse kinematics at intermediate energy. *Phys. Rev. Lett.*, 78:2313–2316, Mar 1997.

[4] A.A. Korsheninnikov, E.Yu. Nikolskii, C.A. Bertulani, S. Fukuda, T. Kobayashi, E.A. Kuzmin, S. Momota, B.G. Novatskii, A.A. Ogloblin, A. Ozawa, V. Pribora, I. Tanihata, and K. Yoshida. Scattering of radioactive nuclei 6he and 3h by protons: Effects of neutron skin and halo in 6he, 8he, and 11li. *Nuclear Physics A*, 617(1):45–56, 1997.

[5] A Lagoyannis, F Auger, A Musumarra, N Alamanos, E.C Pollacco, A Pakou, Y Blumenfeld, F Braga, M La Commara, A Drouart, G Fioni, A Gillibert, E Khan, V Lapoux, W Mittig, S Ottini-Hustache, D Pierroutsakou, M Romoli,

P Roussel-Chomaz, M Sandoli, D Santonocito, J.A Scarpaci, J.L Sida, T Suomijärvi, S Karataglidis, and K Amos. Probing the 6he halo structure with elastic and inelastic proton scattering. *Physics Letters B*, 518(1):27–33, 2001.

[6] M.D. Cortina-Gil, A. Pakou, N. Alamanos, W. Mittig, P. Roussel-Chomaz, F. Auger, J. Barrette, Y. Blumenfeld, J.M. Casandjian, M. Chartier, F. Dietrich, V. Fekou-Youmbi, B. Fernandez, N. Frascaria, A. Gillibert, H. Laurent, A. Lepine-Szily, N. Orr, V. Pascalon, J.A. Scarpaci, J.L. Sida, and T. Suomijarvi. Charge-exchange reaction induced by 6he and nuclear densities. *Nuclear Physics A*, 641(3):263–270, 1998.

[7] T. Aumann, D. Aleksandrov, L. Axelsson, T. Baumann, M. J. G. Borge, L. V. Chulkov, J. Cub, W. Dostal, B. Eberlein, Th. W. Elze, H. Emling, H. Geissel, V. Z. Goldberg, M. Golovkov, A. Grünschloß, M. Hellström, K. Hencken, J. Holeczek, R. Holzmann, B. Jonson, A. A. Korshenninikov, J. V. Kratz, G. Kraus, R. Kulessa, Y. Leifels, A. Leistenschneider, T. Leth, I. Mukha, G. Münzenberg, F. Nickel, T. Nilsson, G. Nyman, B. Petersen, M. Pfützner, A. Richter, K. Riisager, C. Scheidenberger, G. Schrieder, W. Schwab, H. Simon, M. H. Smedberg, M. Steiner, J. Stroth, A. Surowiec, T. Suzuki, O. Tengblad, and M. V. Zhukov. Continuum excitations in ^{6}He. *Phys. Rev. C*, 59:1252–1262, Mar 1999.

[8] X. Mougeot, V. Lapoux, W. Mittig, N. Alamanos, F. Auger, B. Avez, D. Beaumel, Y. Blumenfeld, R. Dayras, A. Drouart, C. Force, L. Gaudefroy, A. Gillibert, J. Guillot, H. Iwasaki, T. Al Kalanee, N. Keeley, L. Nalpas, E.C. Pollacco, T. Roger, P. Roussel-Chomaz, D. Suzuki, K.W. Kemper, T.J. Mertzimekis, A. Pakou, K. Rusek, J.-A. Scarpaci, C. Simenel, I. Strojek, and R. Wolski. New excited states in the halo nucleus 6he. *Physics Letters B*, 718(2):441–446, 2012.

[9] M.S. Golovkov, L.V. Grigorenko, G.M. Ter-Akopian, A.S. Fomichev, Yu.Ts. Oganessian, V.A. Gorshkov, S.A. Krupko, A.M. Rodin, S.I. Sidorchuk, R.S. Slepnev, S.V. Stepantsov, R. Wolski, D.Y. Pang, V. Chudoba, A.A. Korsheninnikov, E.A. Kuzmin, E.Yu. Nikolskii, B.G. Novatskii, D.N. Stepanov, P. Roussel-Chomaz, W. Mittig, A. Ninane, F. Hanappe, L. Stuttgé, A.A. Yukhimchuk, V.V. Perevozchikov, Yu.I. Vinogradov, S.K. Grishechkin, and S.V. Zlatoustovskiy. The 8he and 10he spectra studied in the (t,p) reaction. *Physics Letters B*, 672(1):22–29, 2009.

[10] Isao Tanihata, Herve Savajols, and Rituparna Kanungo. Recent experimental progress in nuclear halo structure studies. *Progress in Particle and Nuclear Physics*, 68:215–313, 2013.

[11] G.D. Alkhazov, A.V. Dobrovolsky, P. Egelhof, H. Geissel, H. Irnich, A.V. Khanzadeev, G.A. Korolev, A.A. Lobodenko, G. Münzenberg, M. Mutterer, S.R. Neumaier, W. Schwab, D.M. Seliverstov, T. Suzuki, and A.A. Vorobyov. Nuclear matter distributions in the 6he and 8he nuclei from differential cross sections for small-angle proton elastic scattering at intermediate energy. *Nuclear Physics A*, 712(3):269–299, 2002.

[12] F. Skaza, V. Lapoux, N. Keeley, N. Alamanos, F. Auger, D. Beaumel, E. Becheva, Y. Blumenfeld, F. Delaunay, A. Drouart, A. Gillibert, L. Giot, E. Khan, L. Nalpas,

A. Pakou, E. Pollacco, R. Raabe, P. Roussel-Chomaz, K. Rusek, J.-A. Scarpaci, J.-L. Sida, S. Stepantsov, and R. Wolski. Low-lying states and structure of the exotic 8he via direct reactions on the proton. *Nuclear Physics A*, 788(1):260–265, 2007. Proceedings of the 2nd International Conference on Collective Motion in Nuclei under Extreme Conditions.

[13] N. Keeley, F. Skaza, V. Lapoux, N. Alamanos, F. Auger, D. Beaumel, E. Becheva, Y. Blumenfeld, F. Delaunay, A. Drouart, A. Gillibert, L. Giot, K.W. Kemper, L. Nalpas, A. Pakou, E.C. Pollacco, R. Raabe, P. Roussel-Chomaz, K. Rusek, J.-A. Scarpaci, J.-L. Sida, S. Stepantsov, and R. Wolski. Probing the 8he ground state via the 8he(p,t)6he reaction. *Physics Letters B*, 646(5):222–226, 2007.

[14] M. V. Zhukov, A. A. Korsheninnikov, and M. H. Smedberg. Simplified α+4n model for the ^{8}He nucleus. *Phys. Rev. C*, 50:R1–R4, Jul 1994.

[15] A. A. Korsheninnikov, E. Yu. Nikolskii, E. A. Kuzmin, A. Ozawa, K. Morimoto, F. Tokanai, R. Kanungo, I. Tanihata, N. K. Timofeyuk, M. S. Golovkov, A. S. Fomichev, A. M. Rodin, M. L. Chelnokov, G. M. Ter-Akopian, W. Mittig, P. Roussel-Chomaz, H. Savajols, E. Pollacco, A. A. Ogloblin, and M. V. Zhukov. Experimental evidence for the existence of ^{7}H and for a specific structure of ^{8}He. *Phys. Rev. Lett.*, 90:082501, Feb 2003.

[16] L. V. Grigorenko, M. S. Golovkov, G. M. Ter-Akopian, A. S. Fomichev, Yu. Ts. Oganessian, V. A. Gorshkov, S. A. Krupko, A. M. Rodin, S. I. Sidorchuk, R. S. Slepnev, S. V. Stepantsov, R. Wolski, D. Y. Pang, V. Chudoba, A. A. Korsheninnikov, E. A. Kuzmin, E. Yu. Nikolskii, B. G. Novatskii, D. N. Stepanov, P. Roussel-Chomaz, W. Mittig, A. Ninane, F. Hanappe, L. Stuttgé, A. A. Yukhimchuk, V. V. Perevozchikov, Yu. I. Vinogradov, S. K. Grishechkin, and S. V. Zlatoustovskiy. Soft dipole mode in 8he. *Physics of Particles and Nuclei Letters*, 6(2):118–125, Mar 2009.

[17] R. Kanungo, A. Sanetullaev, J. Tanaka, S. Ishimoto, G. Hagen, T. Myo, T. Suzuki, C. Andreoiu, P. Bender, A. A. Chen, B. Davids, J. Fallis, J. P. Fortin, N. Galinski, A. T. Gallant, P. E. Garrett, G. Hackman, B. Hadinia, G. Jansen, M. Keefe, R. Krücken, J. Lighthall, E. McNeice, D. Miller, T. Otsuka, J. Purcell, J. S. Randhawa, T. Roger, A. Rojas, H. Savajols, A. Shotter, I. Tanihata, I. J. Thompson, C. Unsworth, P. Voss, and Z. Wang. Evidence of soft dipole resonance in ^{11}Li with isoscalar character. *Phys. Rev. Lett.*, 114:192502, May 2015.

[18] J. Tanaka, R. Kanungo, M. Alcorta, N. Aoi, H. Bidaman, C. Burbadge, G. Christian, S. Cruz, B. Davids, A. Diaz Varela, J. Even, G. Hackman, M.N. Harakeh, J. Henderson, S. Ishimoto, S. Kaur, M. Keefe, R. Krücken, K.G. Leach, J. Lighthall, E. Padilla Rodal, J.S. Randhawa, P. Ruotsalainen, A. Sanetullaev, J.K. Smith, O. Workman, and I. Tanihata. Halo-induced large enhancement of soft dipole excitation of 11li observed via proton inelastic scattering. *Physics Letters B*, 774:268 – 272, 2017.

[19] R. A. Broglia, F. Barranco, G. Potel, and E. Vigezzi. Characterization of vorticity in pygmy resonances and soft-dipole modes with two-nucleon transfer reactions. *Eur. Phys. J. A*, 55:243, 2019.

[20] R A Broglia, F Barranco, A Idini, G Potel, and E Vigezzi. Pygmy resonances: what's in a name? *Physica Scripta*, 94(11):114002, aug 2019.

[21] Thierry Stora, Etam Noah, Rastislav Hodak, Tsviki Y. Hirsh, Michael Hass, Vivek Kumar, Kuljeet Singh, Sergey Vaintraub, Pierre Delahaye, Hanna Franberg-Delahaye, Marie-Genevieve Saint-Laurent, and Gerard Lhersonneau. A high intensity 6 he beam for the -beam neutrino oscillation facility. *EPL (Europhysics Letters)*, 98(3):32001, may 2012.

[22] A. Rodriguez, private communication.

[23] Solaris: A solenoidal spectrometer apparatus for reaction studies white paper,https://www.anl.gov/phy/solaris.

[24] G Potel, A Idini, F Barranco, E Vigezzi, and R A Broglia. Cooper pair transfer in nuclei. *Reports on Progress in Physics*, 76(10):106301, oct 2013.

[25] K. Hagino, N. Takahashi, and H. Sagawa. Strong dineutron correlation in ^{8}He and ^{18}C. *Phys. Rev. C*, 77:054317, May 2008.