Probing the halo structure of the 2^- excited state of ^{10}Be through a halo-to-halo transfer reaction

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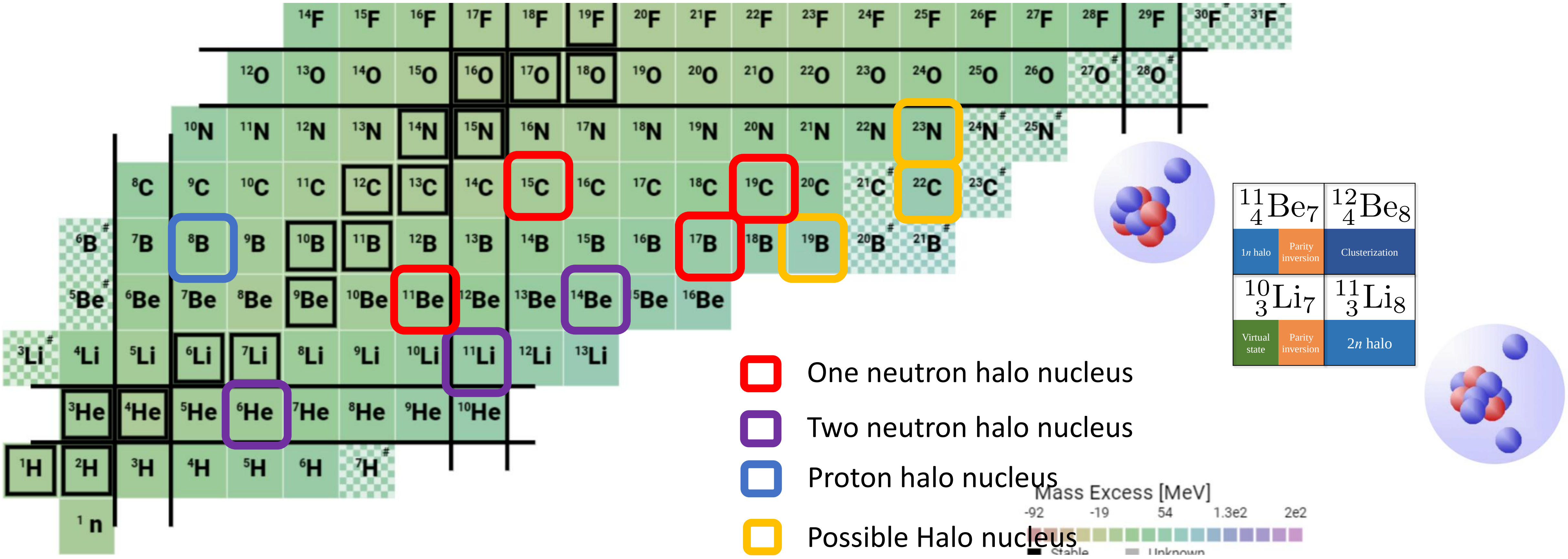
Nuclei with halo

- One neutron halo, two neutron halo, one proton halo nuclei
- New experimental insights on halo nuclei to challenge theoretical predictions.



$^{11}_{4}\mathrm{Be}_{7}$	1n halo	Parity inversion
$^{12}_{4}\mathrm{Be}_{8}$	Clusterization	
$^{10}_{3}\mathrm{Li}_{7}$	Virtual state	Parity inversion
$^{11}_{3}\mathrm{Li}_{8}$	2n halo	

🟥 One neutron halo nucleus

🟪 Two neutron halo nucleus

🟦 Proton halo nucleus

🟨 Possible Halo nucleus

Nuclei with halo

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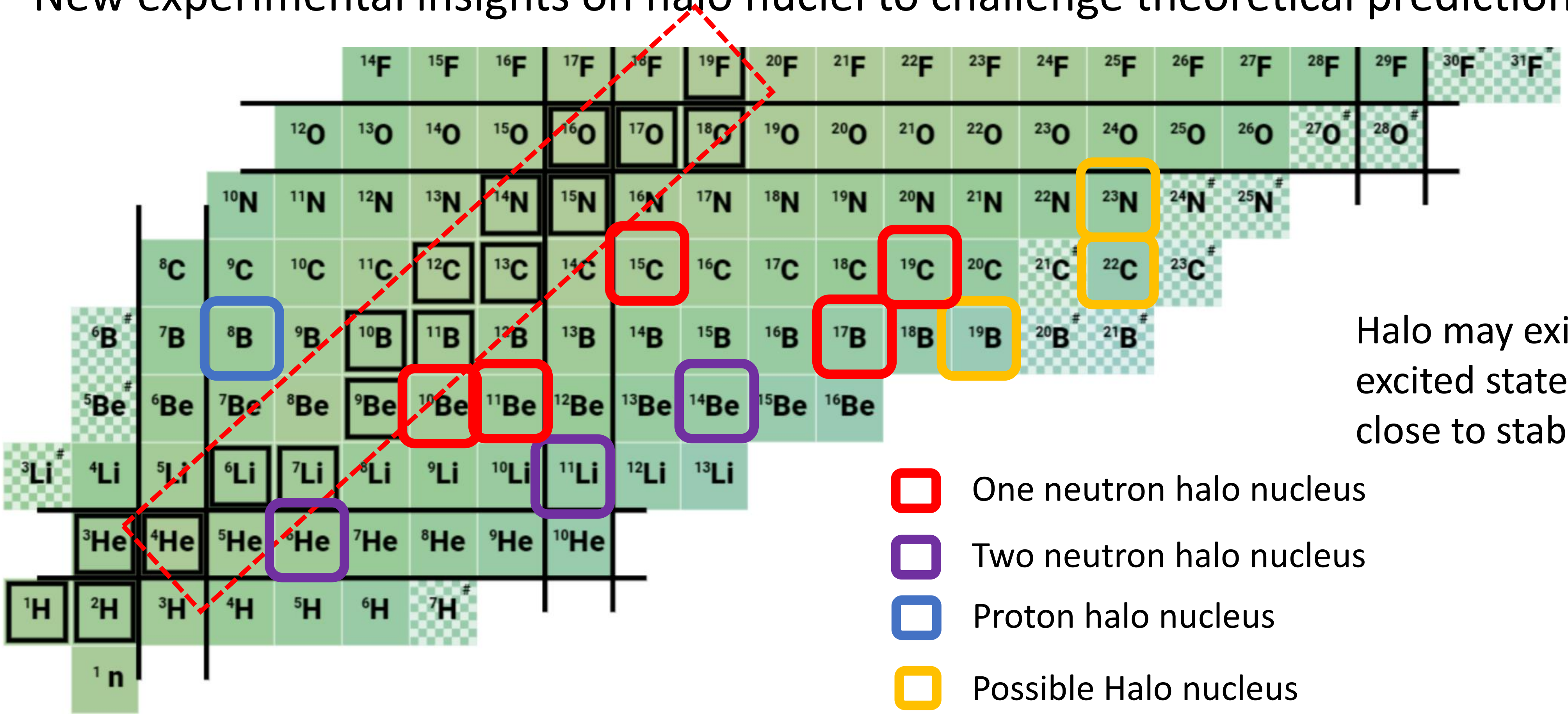


Halo may exist in the excited states of nuclei close to stability

🟥 One neutron halo nucleus

🟪 Two neutron halo nucleus

🟦 Proton halo nucleus

🟨 Possible Halo nucleus

One-neutron halo nucleus ^{11}Be and 2- excited state in ^{10}Be

-- halo in excited states?

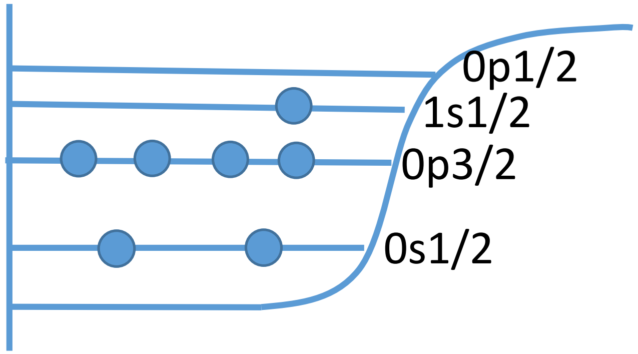
One halo nucleus ^{11}Be:

- Neutron loosely bound Sn=0.504 MeV
- Larger radius R= 2.91 fm
- ^{10}Be core + 1 valance n
- g.s. $1/2^+$

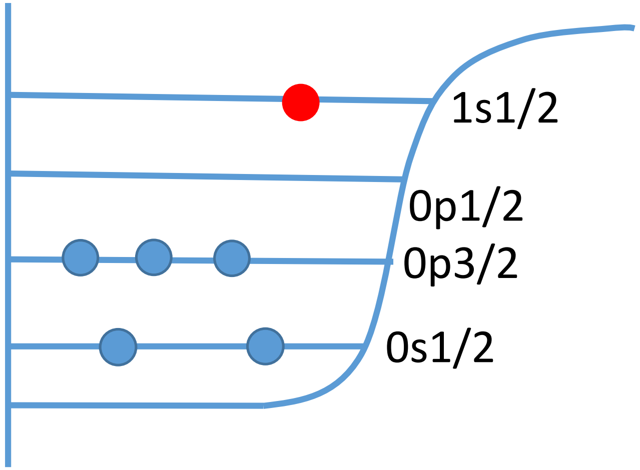
$^{10}\mathrm{Be} + n\ (1s_{1/2})\ (\sim 80\%)$

T. Aumann *et al.* Phys. Rev. Lett. 84, 35 (2000).

K. T. Schmitt *et al.* Phys. Rev.Lett. 108, 192701 (2012).



^{11}Be g.s.



^{10}Be

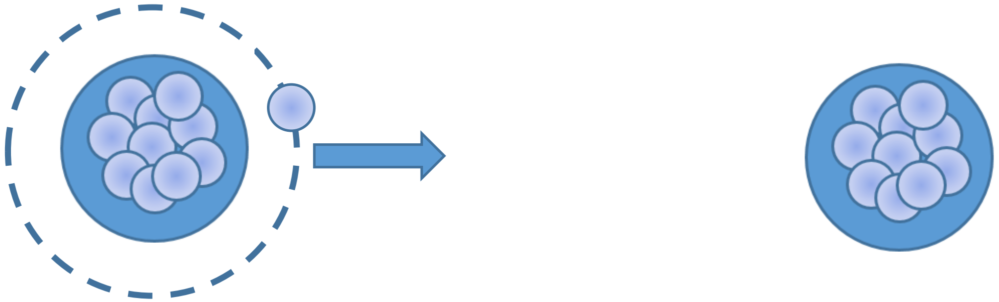
^{10}Be 2- excited state at 6.263 MeV

- 0.549 MeV below S_n
- may exhibit a dominant configuration with one neutron in the $1s_{1/2}$ orbital.

J. Al-Khalili and K. Arai, Phys. Rev. C 74, 034312 (2006)

Halo-to-halo transfer at low energies

--An ideal probe of a halo structure in highly excited states of nuclei.

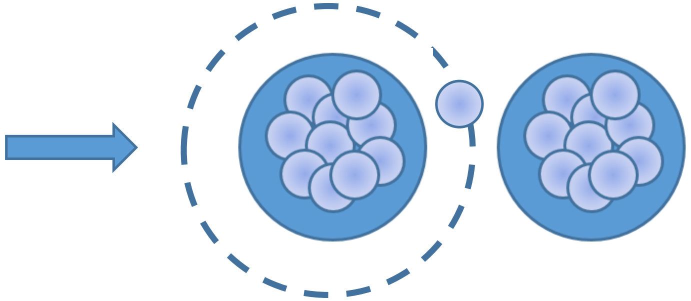


How to realize a halo-to-halo transfer reaction?

- Low energy => cores of colliding nuclei never come close to each other
- If the final state exhibits a halo, the cross section should be significantly larger than if it does not.
- The Q value of the reaction stays positive, so the valence neutron in the incoming nucleus should also be loosely bound.
- To increase the cross section, the magnitude of the tail of its wave function should be as large as possible.

Halo-to-halo transfer at low energies

--An ideal probe of a halo structure in highly excited states of nuclei.



$^{11}\mathrm{Be}+^{9}\mathrm{Be} \rightarrow$ $^{10}\mathrm{Be}+^{10}\mathrm{Be}^{*}(2-)$ At around 3-8 MeV in c.m.

Why this reaction?

- The cores of the colliding nuclei never come close to each other, and only the tail of their wave functions contribute to the reaction. ⟹ low energy reaction
- If the final state exhibits a halo, the cross section should be significantly larger than if it does not.
- To ensure that the Q value of the reaction stays positive, the valence neutron in the incoming nucleus should also be loosely bound. ⟹ $^{11}\mathrm{Be}$
- To increase the cross section, the magnitude of the tail of its wave function should be as large as possible. ⟹ $^{11}\mathrm{Be}$

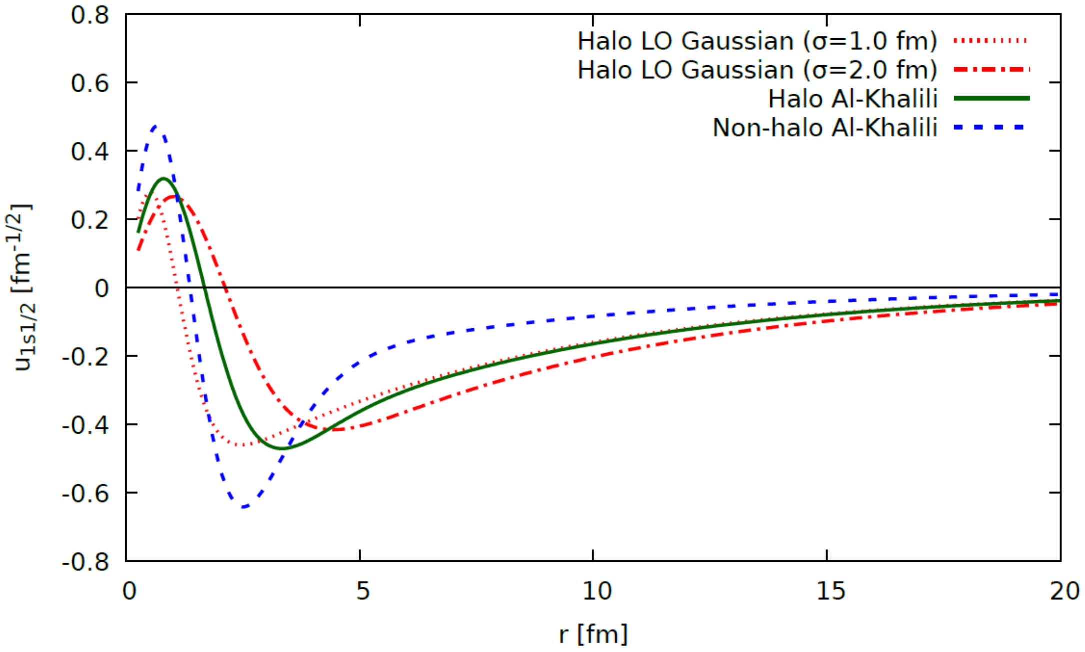
ADWA calculation of ^{9}Be(^{11}Be,^{10}Be)^{10}Be*(2–)

-- Transfer cross sections enhanced by a factor 4, if halo exists

Theoretical three-body model:

- ^{11}Be (projectile): ^{10}Be + n ($1s_{1/2}$)
- ^{9}Be (target): internal structure ignored
- 2– excited state of ^{10}Be (final state): 9Be+n if halo exists
- Halo EFT to describe the halo state
  - Leading order (LO): fitted to the halo-neutron binding energy.
  - Next leading order (NLO): fitted also to the ANC
- ^{10}Be-^{9}Be core-target interaction:
  double-folding of chiral-EFT NN interactions at N2LO

Varying the ANC of the final halo state (^{10}Be* 2-), while keeping the binding energy



P. Capel, D. R. Phillips, and H.-W. Hammer, Phys. Rev. C 98, 034610 (2018)

J. Al-Khalili and K. Arai, Phys. Rev. C 74, 034312 (2006)

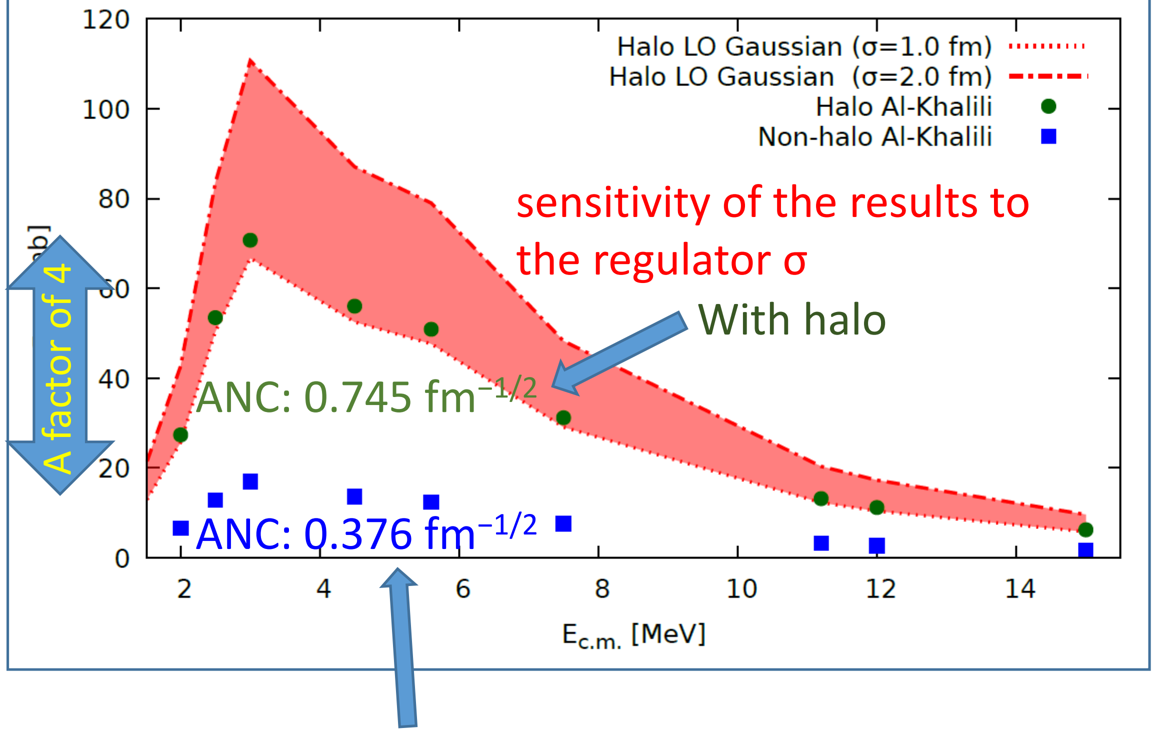
ADWA calculation of ^{9}Be(^{11}Be,^{10}Be)^{10}Be*(2–)

-- Transfer cross sections enhanced by a factor 4, if halo exists

Conclusion of the calculation:

- The cross section scales nearly perfectly with the ANC^2 of the final state
- The reaction is purely peripheral in the ^{9}Be-n and ^{10}Be-n coordinate
- ANC of 0.745 fm$^{-1/2}$ by Al-Khalili and Arai agrees with No Core Shell Model with Continuum model (NCSMC) which gives an ANC of 0.756 fm$^{-1/2}$
- An enhance the cross sections by a factor of 4, if halo exists
- Independent of the optical potential

Integrated one-neutron transfer cross sections at different c.m. energies



sensitivity of the results to the regulator σ

With halo

ANC: 0.745 fm$^{-1/2}$

A factor of 4

ANC: 0.376 fm$^{-1/2}$

Without halo

J. Al-Khalili and K. Arai, Phys. Rev. C 74, 034312 (2006)

Questions raised by the TAC

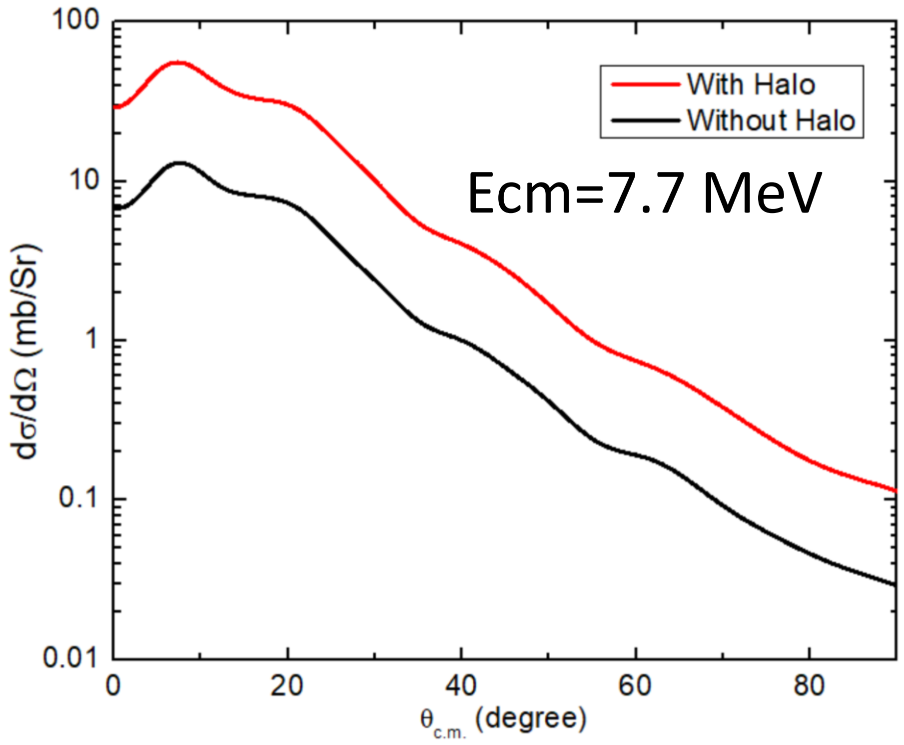
The requested energies are 0.61 and 1.22 MeV/u. These energies are not possible. The alternatives would be 0.3 MeV/u and 1.55 MeV/u. Could this be addressed in the presentation: is the experiment still feasible at these energies? How precise are the energy requirements?

Answer: The experiment will be feasible at 1.55 MeV/u, which corresponds to 7.7 MeV in c.m. frame. At Ecm=1.5MeV, the cross section becomes very small. Therefore we'll require only one beam energy.
The cross section at 7.7 MeV is a little lower than 6 MeV, but the higher energy allows us to use a thicker target. Therefore, the experiment is still feasible.

ADWA calculation of ^{9}Be(^{11}Be,^{10}Be)^{10}Be*(2–)

-- Transfer cross sections enhanced by a factor 4, if halo exists

- The cross sections scale as the ANC^2
- Independent of the optical potential
- The ^{10}Be core and the ^{9}Be target never come close to each other. Excludes the possibility that, instead of the halo-neutron transfer, a deeply bound neutron is transferred from the core to the target



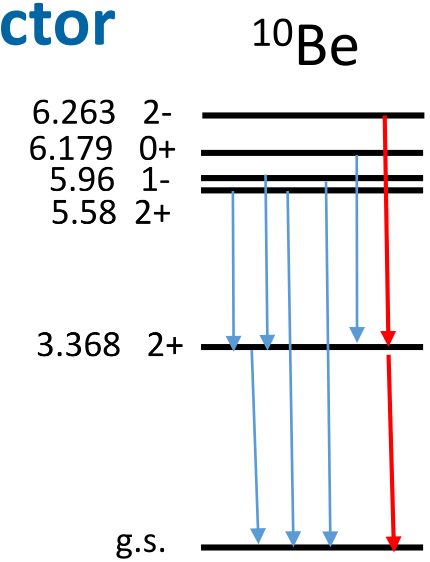
Ecm=7.7 MeV

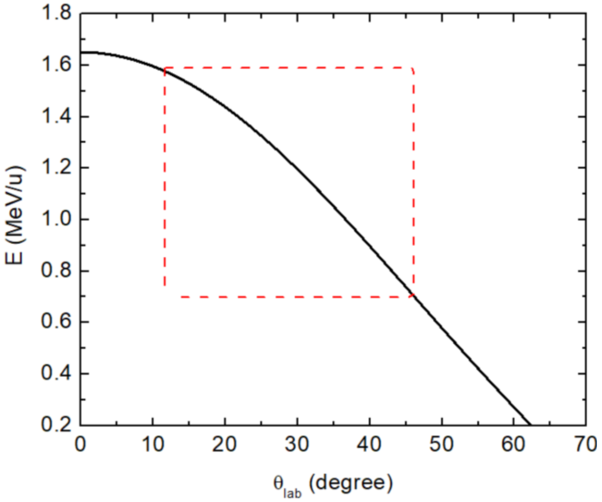
Experimental details

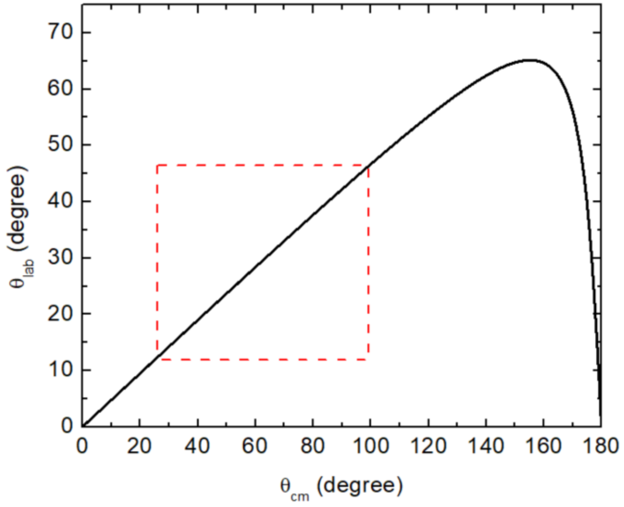
Beam energy:1.55 MeV/u E_{cm}=7.7 MeV

-- MINIBALL+ Silicon detector

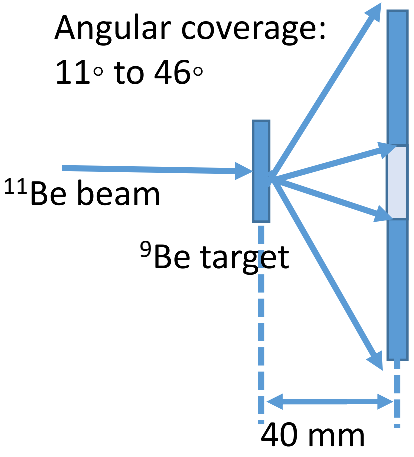
- Tag on the 2.895 MeV γ rays.
- The efficiency of MINIBALL for 2.895 MeV γ ray: ~3%
- The charged particles will be detected by a Compact Disc (CD) double-sided silicon strip detector
- ^{9}Be target thickness 0.8 mg/cm^2
- Beam intensity estimation: elastic scattering cross sections



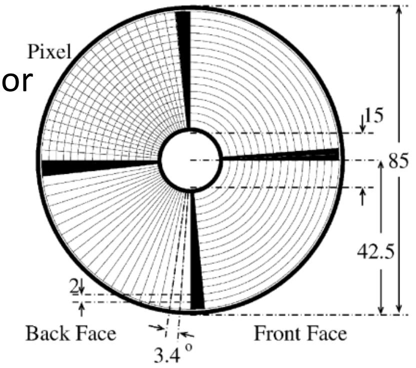




Angular coverage: 11° to 46°

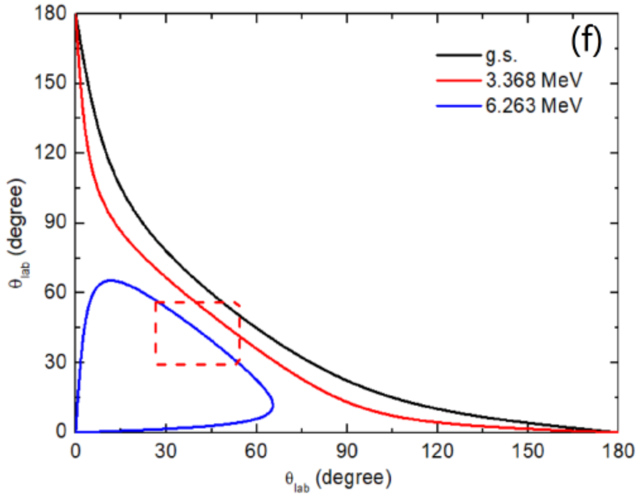


CD detector



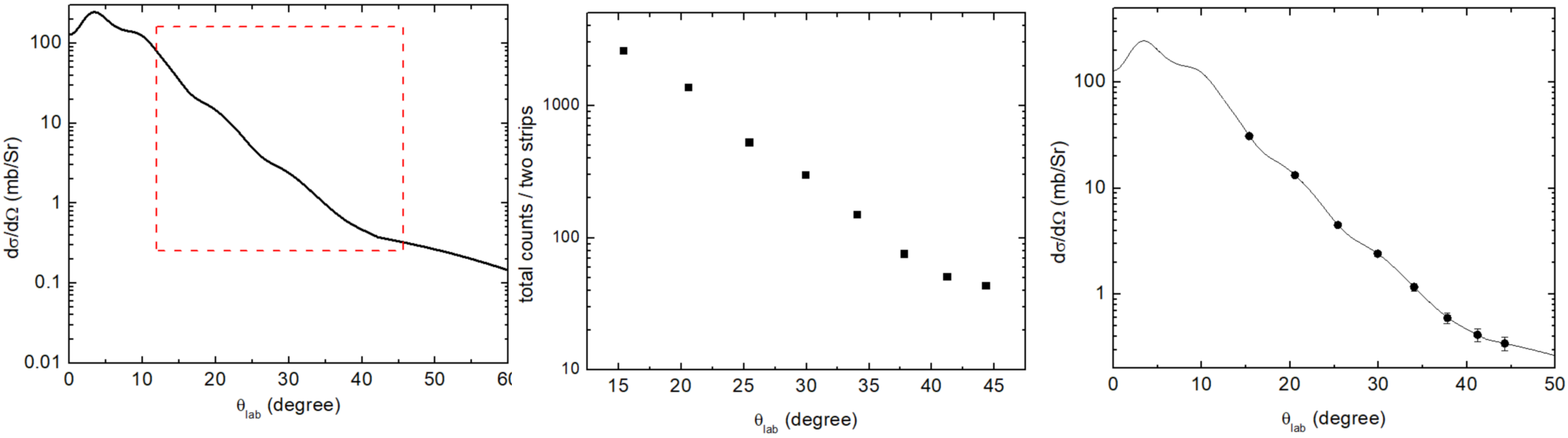
Polar angular Resolution: 1.6°-3.4°

Angular correlation of the Be ions: 27° to 46°



Rates estimation and requested beam time

-- 12 shifts required



- ➢ Estimation based on: Expected beam intensity 10^6 pps, the target thickness 0.8 mg/cm^2, the coincidence efficiency of the γ-ray, and the solid angles of the CD detector
- ➢ 12 shifts required: the total events will be more than 5000 counts for the 2- state.

Summary

Probing the halo structure of the 2^- excited state of ^{10}Be through a halo-to-halo transfer reaction

- The experimental confirmation of the presence of halos in excited nuclear state is difficult. As such, we a measurement of the ^{9}Be(^{11}Be,^{10}Be)^{10}Be*(2−) transfer reaction to investigate the possible existence of a halo in the ^{10}Be(2−) excited state.

- Based on ADWA calculations, the presence of a halo should enhance the cross section by a factor of 4 compared to other excited states. These calculations are independent of the optical potential used and beam normalization.

- ISOLDE coupled to MINIBAL and a set of CD detector array is the ideal combination to study this reaction experimentally. In total, we request **12** shifts of beam time to measure the ^{9}Be(^{11}Be,^{10}Be)^{10}Be*(2−) reaction at 1.55 MeV/u.

Acknowledgement

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