Three-nucleon force effects on the proton elastic scattering with ^{10}C

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Nuclear Force Imprints Revealed on the Elastic Scattering of Protons with ^{10}C

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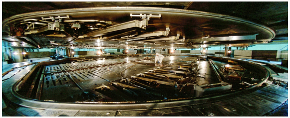
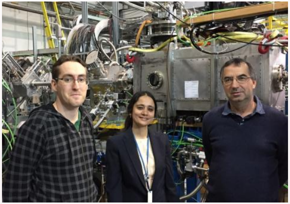
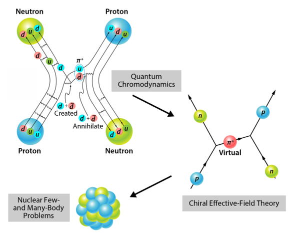
How does nature hold together protons and neutrons to form the wide variety of complex nuclei in the Universe? Describing many-nucleon systems from the fundamental theory of quantum chromodynamics has been the greatest challenge in answering this question. The chiral effective field theory description of the nuclear force now makes this possible but requires certain parameters that are not uniquely determined. Defining the nuclear force needs identification of observables sensitive to the different parametrizations. From a measurement of proton elastic scattering on ^{10}C at TRIUMF and *ab initio* nuclear reaction





Introduction

- Understanding the strong nuclear force is of fundamental importance
- Chiral effective field theory (EFT) helps in understanding of the low-energy nuclear interactions of protons and neutrons
- How to best implement the theory and constrain with experiment?
    - Important to identify experimental observables that are sensitive to different parameterizations of the chiral forces
    - Proton-rich and neutron-rich nuclei located at the edges of nuclear stability (drip-lines), can amplify less-constrained features of the nuclear force (e.g. asymmetry)
    - Experimental data are lacking



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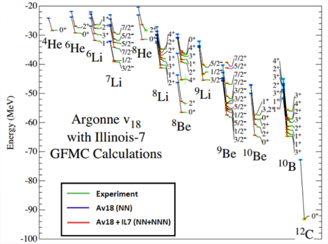
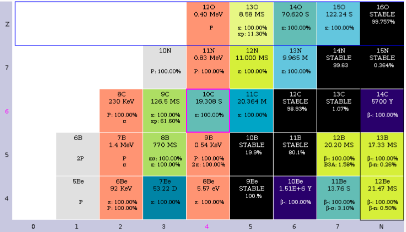
Motivation



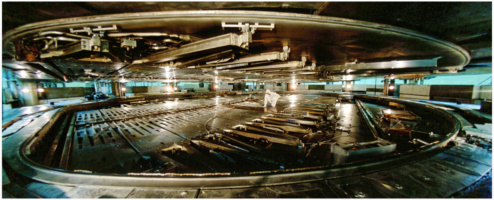
- The nucleon-nucleus scattering differential cross section is highly sensitive to the details of the nuclear force
- It should reveal the spectroscopic properties of the reacting system, as well as the effect of exotic nucleon distributions
- The study of elastic scattering for drip-line nuclei is challenging because of the low-beam intensities and formulation of the ab-initio structure and reaction theory

Motivation



- First investigation probing the nuclear force through proton scattering from ^{10}C (at drip-line)
- Ideal system to test the effect of nuclear force
- Existence of bound ^{10}C whose isotonic neighbours ^{9}B, ^{8}Be and 11N are unbound, is a testament of the complicated strong interaction
- Ab initio Green's function Monte Carlo and no-core shell model (NCSM) calculations have shown 3N forces to be important for explaining the structure of mass number A=10 nuclei
- Low-energy re-accelerated beam available at TRIUMF, our investigation was carried out at low center-of-mass energies
- No-transfer reaction channels are open at low-energy for this system, simplifying ab-initio reaction calculations

Experiment at TRIUMF



- The experiment was performed in inverse kinematics at the ISAC rare isotope beam facility at TRIUMF by bombarding a proton target with a ^{10}C beam
- The beam, re-accelerated using the ISAC-II superconducting linear accelerator, with an average intensity of 2000 particles per second impinged on a solid hydrogen target at the IRIS reaction spectroscopy station
- Energy-loss measured in a low-pressure ionization chamber allowed for clean identification of ^{10}C from the 10B contaminant
- The beam energies at mid-target were 4.54A MeV and 4.82A MeV corresponding to $p+^{10}C$ center of mass energies of Ecm=4.15 MeV and 4.4 MeV, respectively

Experimental Setup for ^{10}C(p,p) at IRIS Facility at TRIUMF

- ^{10}C beam, 5A MeV
- IRIS uses solid hydrogen target
- Maximizes the reaction yield with low-intensity beams
- It was commissioned in 2012 with stable beams and radioactive ^{11}Li beam
- The setup can work with solid H_2 as well as solid D_2 target

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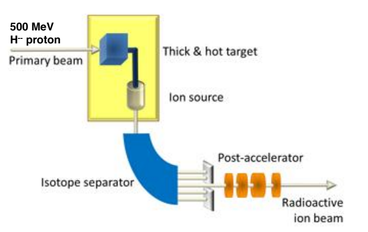
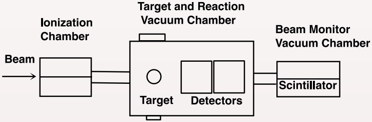
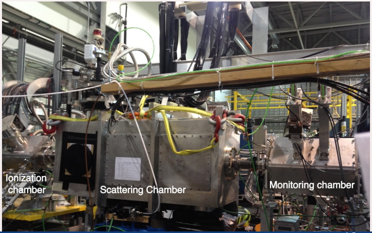
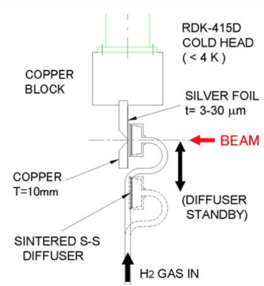
- The setup can work with solid H_2 as well as solid D_2 target
- The low pressure Ionization Chamber (IC) is used for identifying beam contamination before reaction
- Beam particle energy loss is measured event-by-event
- Target and Reaction Vacuum Chamber
    - Solid Hydrogen and target

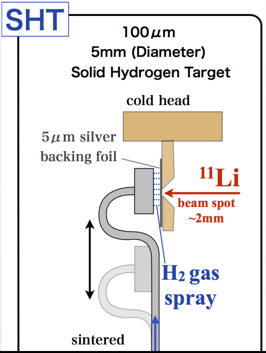


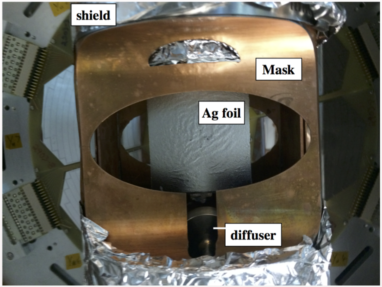




Overview of the Facility: Solid Hydrogen Target

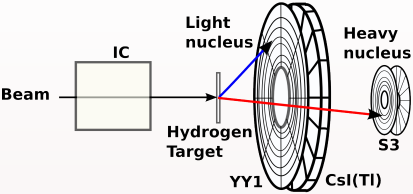




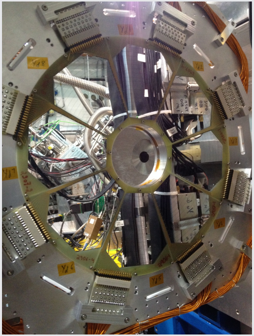


- 30-300 μm solid hydrogen target at 4 K, with 6 mm diameter
- Placed inside the Target and Reaction Vacuum chamber in $\sim$1x10^{-7} Torr vacuum
- Hydrogen gas is sprayed and condensated onto 5 μm Ag foil at 4 K through a diffuser
- Heat shield used for reducing the radiative

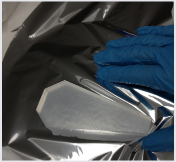
Overview of the Facility: Detectors

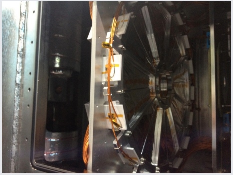


YY1 (LEDA) Detectors



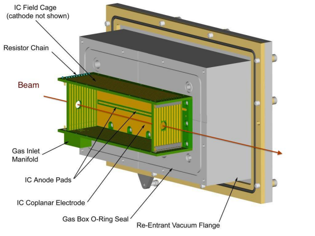
CsI(Tl) detectors



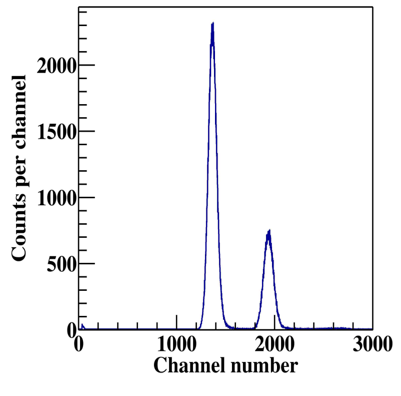


S3 Detectors

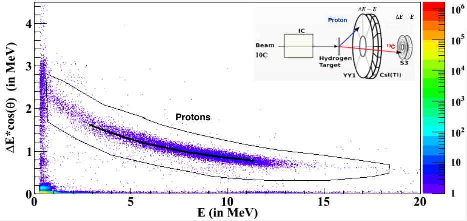
^{10}C identification in the low pressure ionization chamber (IC)

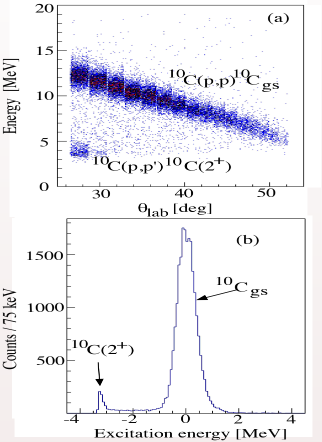


- Beam is a cocktail of ^{10}C (right) and isobaric contaminant ^{10}B (left)
- The contaminant was identified using the energy-loss measured with IC filled with isobutane gas
- The total intensity of the incident beam is measured in the IC



^{10}C(p,p) elastic scattering events





- Protons identified using $\Delta E - E$ method
- The selected proton events show a very clear locus of elastic scattering
- The inelastic scattering locus is only slightly visible

Theoretical models

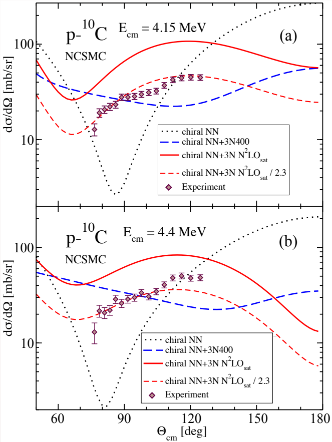
- Our theoretical description of the $^{10}C(p,p)$ scattering is based on the ab initio no-core shell model with continuum (NCSMC)
- This approach describes the reacting system using a basis expansion with two key components:
  - ^{11}N
  - $^{10}C + p$
  - The chiral two-nucleon (NN) and three-nucleon (3N) forces served as input for the NCSMC calculations

Theoretical models

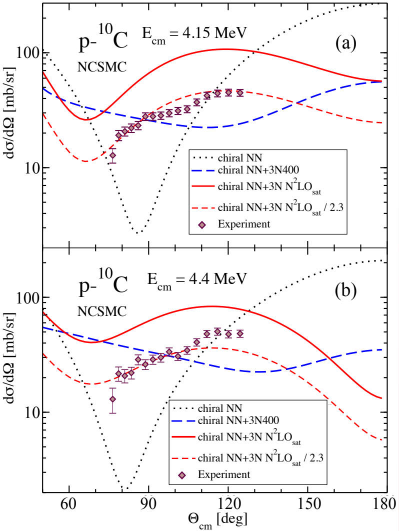
- The NN interaction is tuned to nucleon-nucleon phase shifts and the deuteron properties
- Traditionally, the fit of the NN parameters was performed first, and the 3N parameters adjusted later (NN+3N400)
- Recently, simultaneous NN+3N fit was performed (N^2LOsat)
  - Describes well the proton radius of the stable nucleus
  - and the nuclear radii of neutron-rich carbon isotopes

Results: Differential cross section

- The experimental data contain both statistical and systematic uncertainties
- The systematic uncertainties are as follows : 5% from the target thickness, 5% from determination of the detection efficiency, and 4 % from the beam contamination
- The cross-sections have similar shape and magnitude at the two different beam energies
- Ab initio reaction theory calculations with three different choices of the nuclear force are shown by the curves



- We test 2 parameterizations of chiral NN+3N
- Compare 3N force with a chiral NN interaction alone
- Addition of 3N forces produces dramatic change
- This shows the strong influence of the three-nucleon interaction on the angular distribution



Measured differential cross section for (a) $E_{cm} = 4.15$ MeV and (b) $E_{cm} = 4.4$ MeV

Summary

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- This suggests that N^2LO_{sat} is improved compared to the other forces but is still not an adequate description of the nuclear force
- Extreme systems, such as the ^{11}N and ^{10}C(p,p) investigated here both experimentally and theoretically, thus provide one of the most stringent tests of the quality of the present and new generations of nuclear forces.

Collaborators

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Thanks for attention!