# Cluster Production in MoNA Through Charge Exchange

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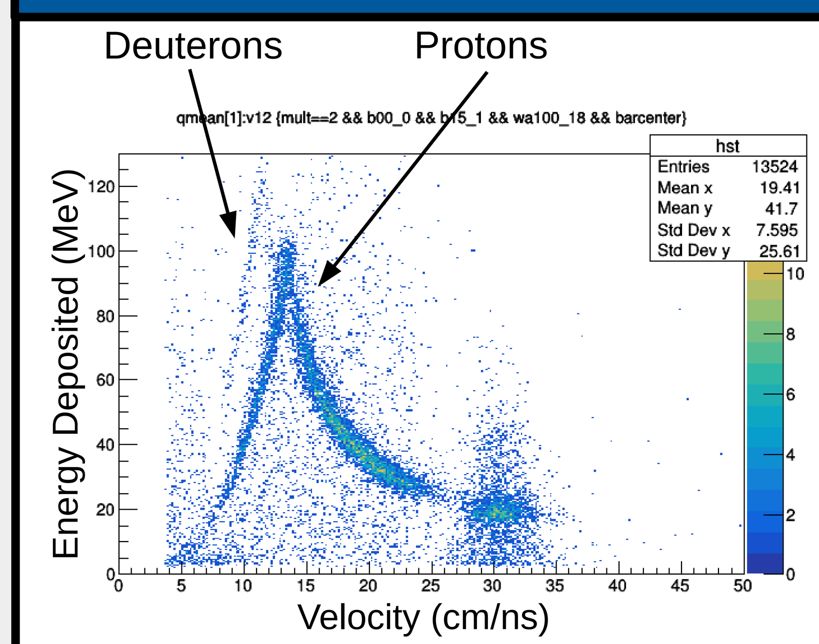
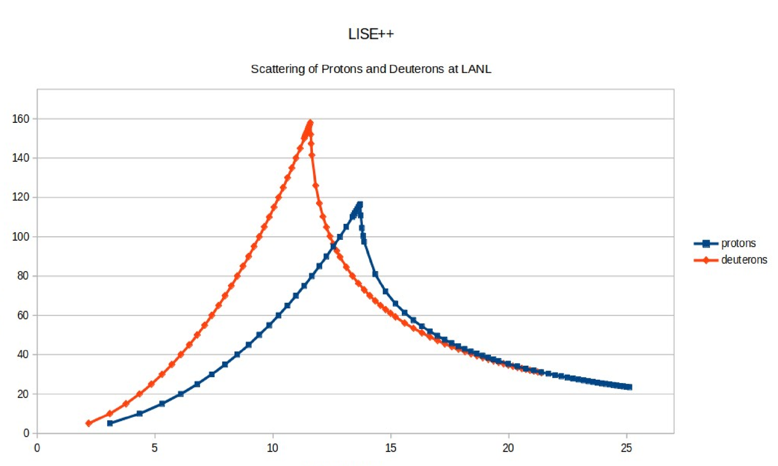
## LANL Experiment

The MoNA Collaboration is a collection of mostly undergraduate institutions dedicated to studying neutron unbound isotopes along the neutron drip line. In 2019, the Collaboration conducted an experiment at Los Alamos National Laboratory to study neutron dark scattering within the Modular neutron array (MoNA) bars. One of the takeaways from this experiment was a confirmation on our understanding of how protons are produced and scatter inside MoNA, and the observation of how array gaps can provide increased resolution of these events.

## Protons and Deuterons

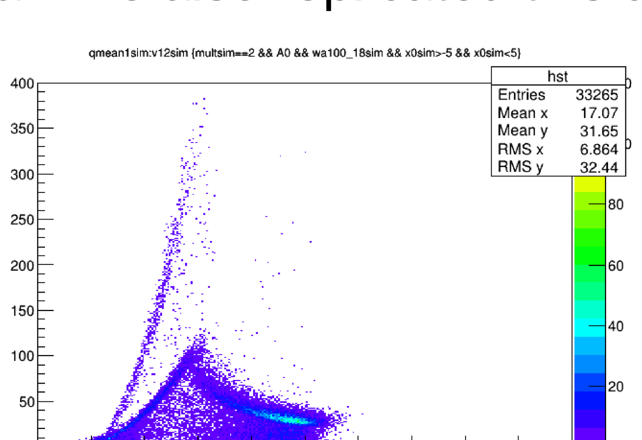



LISE++ simulation of protons and deuterons

- x-axis: Velocity between a hit in the target bar and the ramp.
- y-axis: q (energy) deposited in the hit in the back wall.

In most MoNA experiments, charge exchange in the bars only produce clusters, but when a gap is introduced into an array, we begin to see distinct bands. Using the LISE++ simulation software, we confirmed that the strong band resulted from protons, and the week band was a product of deuterons scattering from the target bar. We also replicated this data with MENATE_R simulation.



MENATE_R simulation

- MENATE_R simulation: Does an excellent job replicating how protons behave, but does not adequately represent deuterons.
- LISE++ comparison to data below:

**Protons**

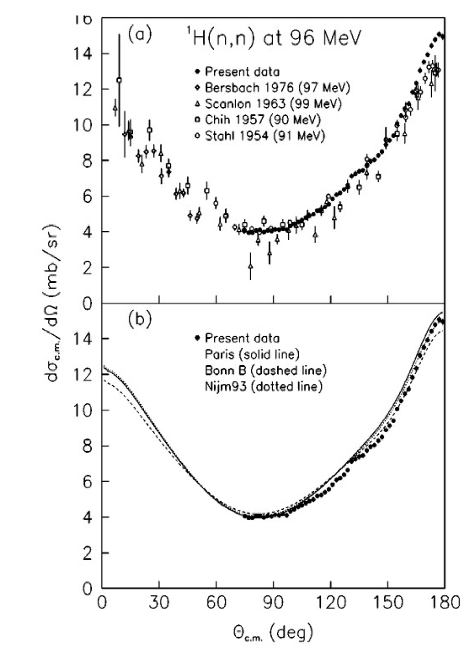
Experiment: 13.3 cm/ns
LISE++: 13.7 cm/ns
Percent Difference: 3.17%

**Deuterons**

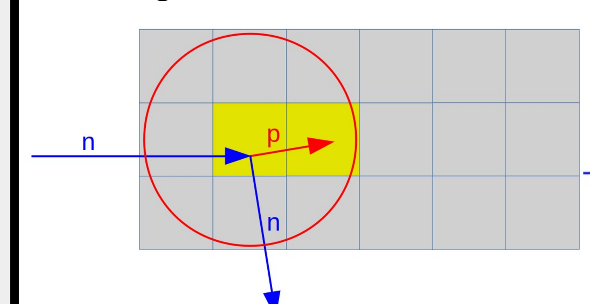
Experiment: 11.4 cm/ns
LISE++: 13.6 cm/ns
Percent Difference: 1.75%

## np Charge Exchange and Clusters

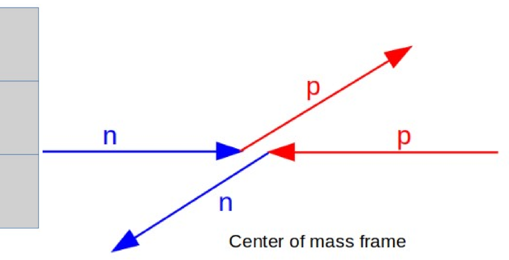
Charge exchange takes place when an incoming neutron swaps quarks with a Hydrogen proton inside of a MoNA bar. This interaction causes the two particles to swap identities. The end result is a high energy, outgoing proton as well as a low energy outgoing neutron. When the proton creates an additional hit in an adjacent bar, we get a cluster event as shown below.



The plot above shows the np cross-section as a function of angle in the center of mass.




Charge exchange in the lab frame (cluster event)

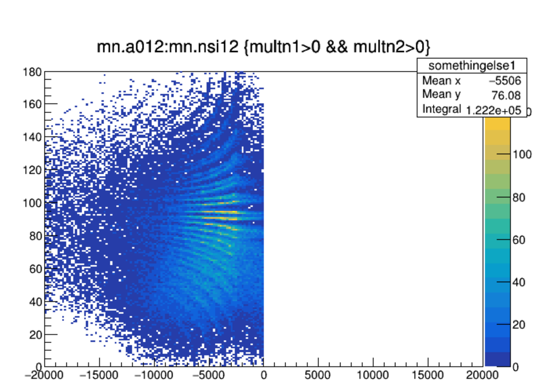


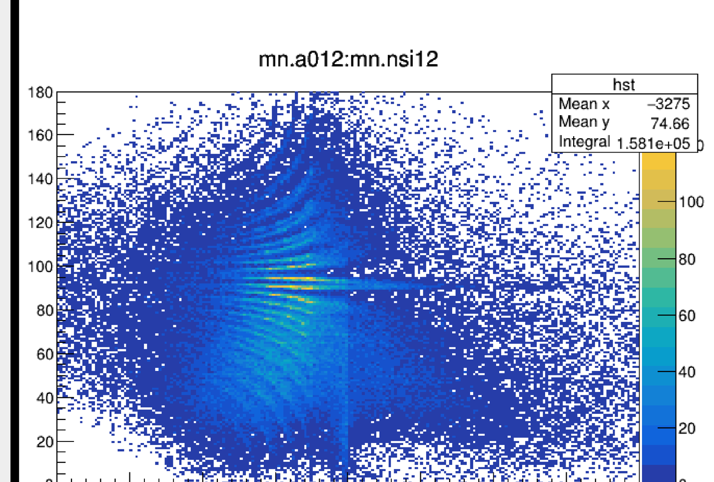

Charge exchange in the center of mass frame

## 2n Filter Using Cluster Correlations

Because of the large amount of energy lost by the neutron producing a cluster event, it's unlikely that it can then create an additional cluster. Therefore, we can filter 2n scatters by looking for cluster-cluster events. Furthermore, a single neutron that creates a cluster has very limited energy. Searching for clusters followed by singlet scatters which deposit light above a large threshold in MoNA is another means of distinguishing 1n from 2n data. Ultimately, these filters help us retrieve 2n data in the causal region as described below.

- Neutron space-time interval (nsi) $\rightarrow$ $nsi = v_{beam}^2 t_{12}^2 - p_{12}^2$

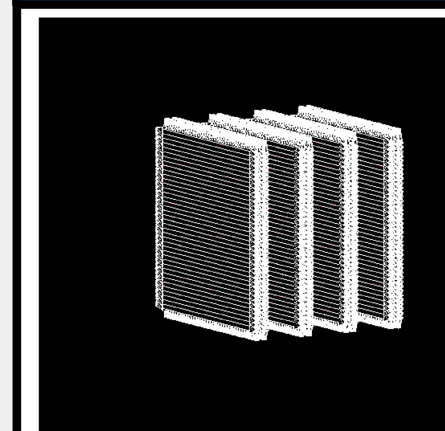





Yield of dd and ds rescues in the causal region.

- The angle vs. nsi plots to the left show the causal connection between two hits. The left half of the plot is the non-causal region while the right corresponds to causal events.
- Cutting out the causal region is a way of filtering out 1n data. However, many 2n events get cut out with this causal filter.
- Searching for two clusters (dd) and a cluster followed by a single hit with high q (ds) as described above, we can resurrect many of the lost 2n data points.
- Using this filter, we keep about 80% of all 2n data.

## Future Array Designs

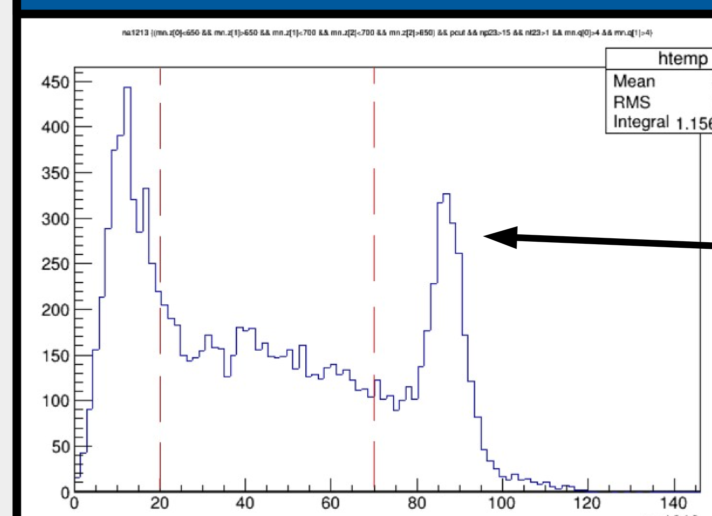


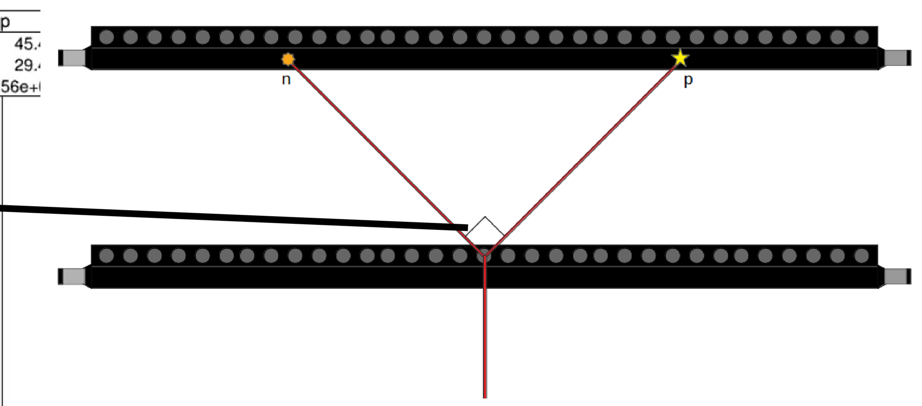
New Array design used in analysis

Using what we learned about protons in the LANL experiment, I worked on developing a design for a next generation MoNA array. This new design includes array gaps for increased resolution as well as smaller bars.

- Bar size: 5 x 5 x 200 cm
- Gap sizes ranged from 20 to 60 cm.

## 2n Filter Using Charge Exchange

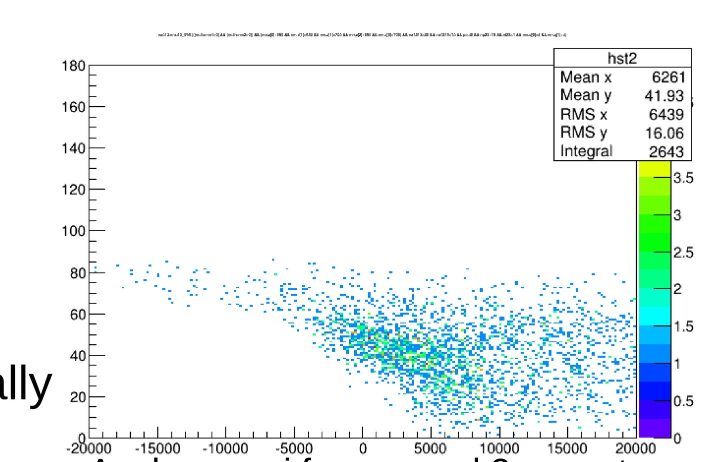





Trajectory of charge-exchange protons and neutrons.

Another filter that we've been developing uses protons traveling across the gap to distinguish between 1 and 2-neutron events. By tracking the proton across the gap and searching for other hits in the second wall, we can eliminate 1n scatters by filtering out the correlated neutrons, which travel 90 degrees relative to the proton's trajectory.

- 90 degree peak produced by neutrons correlated with the detected protons.
- 20-70 degree region contains mostly uncorrelated neutrons (2n data).
- Low degree peak results from hits causally connected to proton interactions.



Angle vs. nsi for rescued 2n events

- regains about 1% of 2n data in 90-100 MeV range

## Future Developments

- Moving to higher energies at FRIB will increase the yield of cluster events so that more 2n events can be recovered.
- Incorporating the cluster-cluster and charge exchange filter in the multi-neutron code. (refer to Andrea Munroe's poster)

## Acknowledgements

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