Motivation

Understanding the exact nature of the nuclear force is one of the long-standing questions in nuclear physics. Time-line of progress in few-body nuclear physics:

- **Two-nucleon (2N) System**: Yukawa in 1935 proposed meson-exchange theory of two interacting nucleons. It was proved in 1947 with the discovery of Pions. Today there exists many theoretical models to accurately describe all the nucleon-nucleon (NN) scattering data. Some of these most used models, for example, are Nijm-I,-II, Argonne v18, CDBonn...

- **Three-nucleon (3N) System**: In the past few decades, the three-nucleon (3N) systems have been studied extensively in both, theoretical and experimental aspects. With the new and improved experimental facilities, the measurement of very subtle effects such as the three-nucleon force (3NF) in the 3N system has now become possible. Theoretical treatment of the 3N systems dynamics have also progressed in parallel.

- **What’s the next ... four-nucleon (4N) system**: The available large sets of high-precision 3N data are quite well described by the models. For more complicated systems, such as four-nucleon (4N), the knowledge is scarce in both, the theoretical and the experimental domain. Recently certain progress have been made in calculations of 4N system, but so far at the energies below the breakup-reaction threshold in dd collision.

What we can do: ... provide the new and improved experimental facilities, the measurement of very subtle effects such as the three-nucleon force (3NF) in the 3N system has now become possible. Theoretical treatment of the 3N systems dynamics have also progressed in parallel.

Some basics steps of analysis:

- Traditional $\Delta E-E$ technique was applied for the particle identification. Multi wire proportional chamber (MWPC) was used for position reconstruction of the scattered charged particles.

- Following reaction channels were identified:

  - $d+d\rightarrow d+d$ (elastic scattering)
  - $d+d+p+n$ (three-body breakup)
  - $d+d+p+n+\text{spectator}$ (two-spectator QFS)
  - $d+d+H+{n}$ (neutron transfer)

- Exception: Relatively low rates of hadronic interaction of the scattered neutrons with the scintillator allows to detect the proton transfer channel $d+d\rightarrow H+{n}$

- Cut on the relative $\phi$ around $\pm180^\circ$ allows to extract coincidence of two co-planar charged particles.

- Further cuts on particle types allows to distinguish the elastic channels and the QFS channel:

  - Two-body kinematics
  - Three-body kinematics

Three-body kinematics:

- Conservation of total energy and momentum allows to study three-body breakup reaction based on two particles detection, with the need of five independent variables, namely: $\theta$, $\phi$, $E_1$, $E_2$ and $\phi_D$.

- Example of calculating the S-value along the breakup kinematics for the particles 1 and 2.

Results

Concluding and Outlook

- The obtained precise experimental data in a wide phase space region can serve as a valid tool for verification of rigorous theoretical calculations which are being developed.

- The future studies of the 3N and 4N system dynamics in the breakup reactions with BINA detector @ Cyclotron Centre of Bronowice (CCB) were proposed, making it one of the few leading few-body experimental facilities in the world.

Selected References