

## **The Study of Cold, Dense Nuclear Matter at BNL**

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Neutrons and protons, known collectively as nucleons, attract each other strongly, which is why we have atomic nuclei. However, when nucleons get very close at distances shorter than  $0.4 \text{ fm} = 4 \times 10^{-16} \text{ m}$ , they repel each other strongly, which is why nuclei do not collapse to a point. This repulsion between nucleons at small distances causes all heavy nuclei to have a maximum density at their centers of about  $0.18 \text{ nucleons/fm}^3$ . “Dense nuclear matter” is then a system of nucleons with density higher than this central density. The repulsive inter-nucleon force at small distances has not been investigated enough to exclude the possibility that the repulsive barrier is penetrable and new kinds of dense nuclear matter may exist under special conditions.

At RHIC, experiments produce dense nuclear matter by colliding two heavy nuclei. This produces “hot dense nuclear matter,” where large numbers of nucleons share the kinetic energy and the temperature increases. In nature there exists another way to create dense nuclear matter by using another force to overcome the strong inter-nucleon repulsion at short distances. Neutron stars are huge nuclei with a mass greater than the sun, (about  $10^{57}$  nucleons), a radius of about 10 km, and a density in the center, which is 5 to 10 times the central density of nuclei. This dense nuclear matter is created by the large gravitational force, which adds the necessary compression. Neutron stars are “cold dense nuclear matter;” their temperature is effectively zero.

Brookhaven National Laboratory reported that the study of hot dense nuclear matter at RHIC reveals a “perfect liquid” behavior for hot matter. Here we report on a study of cold nuclear matter performed at BNL, which also reveals surprising results. This study was done by an experiment using the proton beam from the AGS shortly before the AGS became the injector for RHIC. The experiment is E850, with Alan Carroll (BNL) and Steven Heppleman (Penn State) as spokesmen. The collaborating institutions were Tel Aviv University, Kent State University, Yerevan Physics Institute, Petersburg Nuclear Physics Institute, JINR-Dubna, and Mount Holyoke College.

The cold dense nuclear matter that we studied in the laboratory is produced by quantum fluctuations in normal nuclei. For a very brief period of time, two nucleons in a nucleus can be very close to each other and create a small droplet of cold dense nuclear matter with a local density comparable to that assumed for neutron stars. To identify these events we used the idea familiar from the discovery of quarks in “deep inelastic scattering” processes. The experiment selected events where a large amount of momentum was transferred to the two-nucleon droplet. The transferred momentum

should be significantly larger than the minimum value given by the Heisenberg Uncertainty Principle: (transferred momentum) x (radius of droplet) > (Planck's constant)/ $2\pi$ . The expectation is that such a probe may help to resolve the structure of the two-nucleon droplet. This is a promising way to study cold dense nuclear matter, and to study the unique properties of this elusive nuclear matter phase.

We used the EVA spectrometer, which was built at BNL to study large-momentum-transfer proton reactions. The EVA spectrometer, shown in the figure, consists of a 0.8 T superconducting solenoid, 3.3 m long and 2 m in diameter. The AGS proton beam was incident along the central axis. Coincident pairs of high-transverse-momentum protons were detected with four concentric cylinders of "straw-tube" drift chambers.

In a typical event, a proton from the beam struck a proton in a target nucleus, and both protons were detected by the EVA spectrometer. From the momenta of the two detected protons, and the principle of conservation of momentum, we reconstructed the momentum inside the nucleus of the proton that we knocked out. We also looked for neutrons emerging from the target nucleus at the same time as the two detected protons. These neutrons were detected in an array of plastic scintillators mounted below the EVA spectrometer (see figure).

In our experiment, we used beams of 6 to 9 GeV/c protons and a carbon target (99%  $^{12}\text{C}$ ). We found that when we knocked a proton out of a target nucleus with reconstructed nuclear momentum between 275 and 550 MeV/c, about 50% of the time a neutron emerged from the nucleus with momentum almost equal and opposite in direction to the reconstructed momentum of the detected nuclear proton. After making corrections for the absorption of the incident and detected nucleons in the carbon nucleus, and the motion of the pair in the nucleus, we found that  $92 \pm 18\%$  of the time, the knocked out proton had a coincident neutron with equal and opposite momentum. The relevant range of momenta should depend on atomic number, but the general picture should hold for other nuclei.

These surprising new results were confirmed in a higher-precision experiment completed recently at Jefferson Laboratory in Virginia. In that experiment the protons are knocked out of  $^{12}\text{C}$  nuclei with high-energy electrons. Additional neutrons or protons emerging from the struck nuclei are detected in coincidence with the scattered electron and the knocked-out proton. The results of this recently completed Jefferson Laboratory experiment are fully consistent with the earlier results from AGS experiment E850. Because these experiments were performed in different laboratories, with different types of beams (electrons vs. protons), with different equipment, and by different teams of investigators, the consistency of the results indicates that what has been observed is truly a characteristic of nuclear structure, and not an artifact of the reaction mechanism or the equipment used.

These two experiments lead to a very clear new picture of nuclei:

\* Nucleons in  $^{12}\text{C}$  with momenta up to about 275 MeV/c can be described well as independent particles moving in an average field created by all the other nucleons in the nucleus; this description is conventionally called the “nuclear shell model.” At any given time about 80% of the nucleons in  $^{12}\text{C}$  are undergoing such motion, rather than 100% as is assumed in the nuclear shell model.

\* Nucleons in  $^{12}\text{C}$  with momenta above about 275 MeV/c are almost always organized in pairs. The nucleons in the pair are close to each other and create cold dense local droplets of high-density nuclear matter. About 20% of the nucleons in  $^{12}\text{C}$  are in this state.

\* In  $^{12}\text{C}$ , which has equal numbers of protons and neutrons, there are around 18 times more neutron-proton pairs than proton-proton or neutron-neutron pairs.

\* For neutron stars, where the nucleons are almost all neutrons, these results may help constrain the equation of state.

\* The difference between neutron-proton and neutron-neutron or proton-proton pairs is due to the nature of the nucleon-nucleon interaction. The tensor force in the neutron-proton interaction, which is missing in the neutron-neutron or proton-proton interaction, is probably what creates the difference between cold dense matter of nucleons of the same kind, and cold dense matter of mixed nucleons.

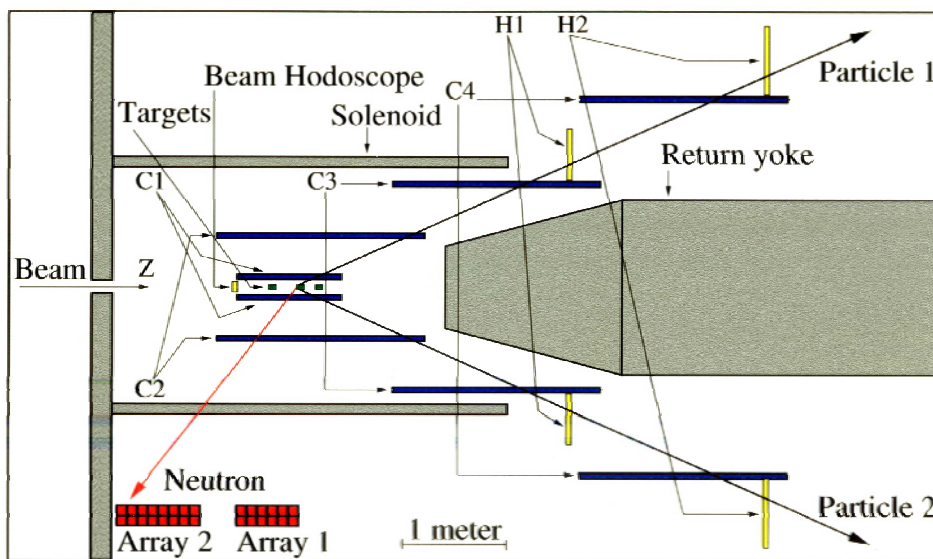


Figure 1: A schematic side view of the EVA spectrometer.