EFFECTS OF ISOSPIN ASYMMETRY AND IN-MEDIUM CORRECTIONS ON BALANCE ENERGY

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The bulk properties of nuclear matter under extreme conditions are of interest to both nuclear physics and astrophysics. To generate these conditions, we collide nuclei in search for hints on the nature of the nucleus-nucleus interaction. Theoretical studies of these events allow us to make a connection between models and experiment though observables such as the balance energy [1]. Balance energy, or the beam energy at which transverse, in-plane directed flow changes sign as a function of beam energy, is sensitive to the forces underlying the dynamics of these collisions. Thus its study can yield valuable information about the complex interplay of the repulsive nature of the hard scattering nucleon cross section, the repulsion and attraction of the nuclear mean field, and the repulsive contribution of the Coulomb force.

Recently, it was experimentally shown [2] that the balance energy for symmetric systems of equal mass has different values for different isospin asymmetry of the colliding nuclei. In this paper we therefore study the isospin-dependence of the balance energy, attempt to isolate its origin, and hope to find sensitivity to the isospin-dependence of the nuclear mean field.

Here we study the influence of the isospin dependent effects in heavy ion collisions on the balance energy [3]. To perform this investigation, we use the Boltzmann-Uehling-Uhlenbeck transport theory with isospin dependent mean field potentials. Two choices were considered, one by B.A. Li [4] and one by L. Sobotka [5].

The Li-potential is

$$U = A\overline{\rho} + B\overline{\rho}^{\sigma} + C\tau_z\delta \tag{1}$$

where $\overline{\rho} = \rho/\rho_0$ (ρ_0 is the normal nuclear density), $\delta = \frac{\rho_n - \rho_p}{\rho_0}$ is the isospin asymmetry (ρ_n is the neutron density, ρ_p is the proton density), and τ_z is the isospin factor which is 1 for neutrons and -1 for protons. The coefficients A, B and σ are typically chosen to match the ground state properties of symmetric nuclear matter such as the saturation density and saturation binding energy. The compressibility is a free parameter, and in this study we chose it to be 200 MeV.

The Sobotka-potential is

$$U_n = \overline{\rho}(4a + 2ab) + \delta(4a - 2ab) - c\delta^2 + 3c\overline{\rho}^2 - 2c\delta\overline{\rho}, \tag{2}$$

for neutrons, and

$$U_p = \overline{\rho}(4a + 2ab) + \delta(2ab - 4a) - c\delta^2 + 3c\overline{\rho}^2 + 2c\delta\overline{\rho}, \tag{3}$$

for protons. a, b and c are again coefficients matched to reproduce saturation conditions. This potential has a compressibility of 380 MeV.

The nucleon-nucleon cross sections are parameterization from the Particle Data Group, with medium modification implemented according to the density dependent prescription:

$$\sigma_{\mathrm{NN}} = \sigma_{\mathrm{NN}}^{\mathrm{free}}\,(1 + \alpha\,\overline{\rho}) \tag{4}$$

where α is the logarithmic derivative of the in-medium cross section with respect to the density, taken at $\rho = 0$ [6].

In Fig. 1, we show the experimental results of Pak *et al.* [2] as the shaded rectangles. The width of these rectangles represent the width of the impact parameter bins used for the integrations of the experimental data. The height of the rectangles represent the error bars in the balance energy (standard deviation of the mean). The darker shaded rectangles represent the experimental results for the ^{58}Fe + ^{58}Fe system, and the lighter gray areas those for the ^{58}Ni + ^{58}Ni. The thick horizontal lines through the middle of each rectangle represent the quoted experimental values. This experimental information is the same in all three panels of Fig. 1, each time compared to a different calculation.

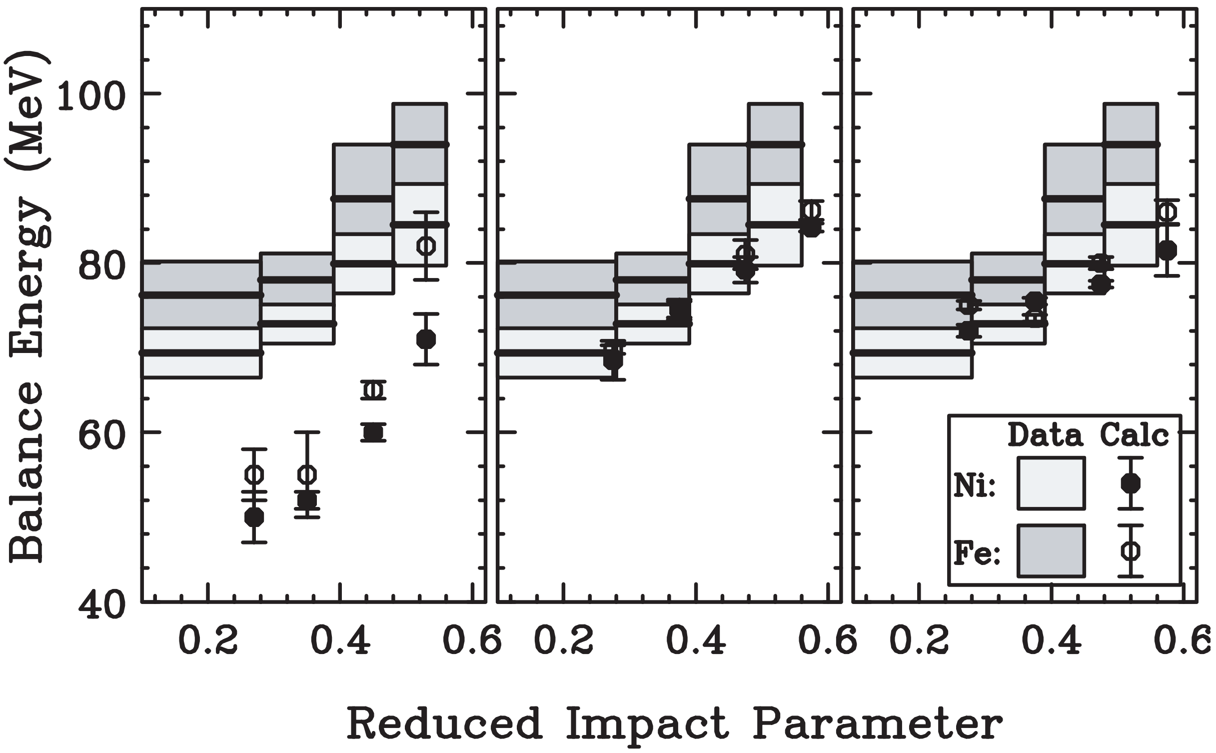

Figure 1: Impact parameter dependence of the balance energy for the systems ^{58}Ni + ^{58}Ni (light shaded rectangles: data; open circles: calculations) and ^{58}Fe + ^{58}Fe (dark shaded rectangles: data; filled circles: calculations). Left panel: results of B.A. Li with free nucleon-nucleon cross sections; middle panel: mean field of B.A. Li and $\alpha = -0.3$; right panel: mean field of Sobotka and $\alpha = -0.2$.

The theoretical results for the ^{58}Fe + ^{58}Fe system are indicated by the open plot symbols, and those for ^{58}Ni + ^{58}Ni by the filled ones.

In the left panel of the figure, we show the result of a calculation with the mean field interaction of B.A. Li [2], and with $\alpha = 0$. Pak *et al.* found that BUU under-predicted the balance energies of ^{58}Fe + ^{58}Fe and ^{58}Ni + ^{58}Ni collisions. This is consistent with previous work [6] that has shown the BUU model utilizing free-space scattering cross sections consistently under-predicting the balance energies of various systems. However, the positive results of Pak *et al.* was the correct reproduction of the differential effect in the balance energies -- the difference between the balance energies for the two systems has the right sign and approximately the right magnitude.

In the central and right panels, we use the isospin dependent mean fields of Li (center) and of Sobotka (right), combined with the in-medium corrections to the elementary two-nucleon scattering cross sections. For the central panel, we use $\alpha = -0.3$, and for the right panel, we use $\alpha = -0.2$, respectively.

Let us first compare the results of the central and the left panel. For both calculations, we use identical isospin-dependent mean fields. The only difference is the change in the scattering in-medium correction. We can make two rather obvious observations: First, the theoretical calculations are much closer to the data when using the in-medium reduction of the scattering cross section -- for all impact parameter intervals. This observation is consistent with previous results that did not look at isospin-dependent effects [1,6]. Second, even though the balance energies for the iron system are still slightly higher than for the nickel system, the magnitude of the splitting has been reduced and is now at least a factor of 4 smaller than what is observed in experiment.

The same effects can be observed when using a different iso-spin dependent mean field, compare the right panel of Fig. 1. Here, the differences between the theoretical balance energies are somewhat larger, but still a factor of at least 2 smaller than those found in the data.

We see an improvement in the performance of the BUU model's prediction of balance energies as a function of impact parameter for collisions of ^{58}Fe + ^{58}Fe and ^{58}Ni + ^{58}Ni by including both an asymmetry energy term in the mean field and in-medium reduction of the nucleon cross section. We observe similar performance among the different formulations used for the mean field. However, the mean field of Bao-An Li, requires $\alpha = -0.3$, whereas the Sobotka formulation, requires $\alpha = -0.2$ for substantial improvement. Efforts to distinguish between these two mean fields will likely come from heavy ion calculations in conjunction with experiments near the drip lines. In the systems studied in the experiments by Pak *et al*, the range in isospin asymmetry was not sufficiently large to constrain our parameter space any further.

We have studied the different contributions of the Coulomb force, the NN-scattering, and the isospin-dependent mean field on the isospin dependence of the balance energy. Our numerical results support the conclusion that the sign and the bulk of the isospin-difference in the balance energies is caused by the difference in the Coulomb interaction and the isospin dependence in the effective nucleon-nucleon two-body scattering.

While we can understand the absolute magnitude of the balance energies and the sign of the isospin-dependent difference between the two systems, our theoretical calculations do not yield the correct absolute magnitude of the difference. One can speculate on the origin of this important disagreement. A lack in our understanding of the isospin dependence of the nuclear mean field or the isospin-dependent in-medium modification of the two-body scattering cross section are the leading candidates. However, there is strong reason to suggest that the higher beam intensities of the radioactive beam facilities currently in planning or under construction will allow us to make progress in our understanding of this problem by enabling us to explore a larger isospin asymmetry in heavy ion reactions.

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