Realistic Nuclear Wave Functions and Heavy Ion Collisions

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In the past decade, various measurements have been unambigously identified two-nucleon Short Range Correlations, studied their structure and related them to the underlying short range Nucleon-Nucleon (NN) interaction (1)-(4). In (1) two- and three-body correlations were studied in large nuclei and related to deuteron and ^3He measurements; the $(p, 2p + n)$ (3) experiment studied the directional correlation between proton and neutron momenta, while in (4) it was shown that about 90% of high momentum protons are correlated with a neutron; in (2) high momentum protons in $(e, e'p)$, $(e, e'pp)$ and $(e, e'pn)$ were investigated, finding a recoling, back-to-back proton in 10% of the events and a neutron in 90% of the events, consistently with (4). After these experiment, several nuclear theory groups showed that the measured ratio is a strong indication of the operation of an NN tensor force in the pair at the nucleon separations and relative momenta studied (5), (6). Recently, an effective many-body approach for the description of ground-state wave functions have been adopted for complex nuclei by the Perugia group, relying on a cluster expansion for the calculation of expectation values of quantum operators on the ground state wave functions with realistic forces (7). In this work, we investigated the effect of correlation on the fraction of potential energy in the nucleus which is carried by the different *pn* and *nn* pairs; moreover, we investigated the possibility of inclusion of full state-dependent correlations in nuclear configurations for the simulation of NA and AA collision at high energies.

We can calculate the potential contribution to the ground state energy according to

$$(1)\quad \langle V\rangle = \sum_{i<j}^{A} \langle \hat{v}(r_{ij})\rangle = \sum_{i<j}^{A}\left\langle \sum_{n=1}^{6} v^{(n)}(r_{ij})\,\hat{O}^{(n)}_{ij}\right\rangle = \frac{A(A-1)}{2}\sum_{n=1}^{6}\int d\mathbf{r}_1 d\mathbf{r}_2\,\rho^{(2)}_n(\mathbf{r}_1,\mathbf{r}_2)\,v^{(n)}(r_{12})\,.$$

Here $\rho^{(2)}_n(\mathbf{r}_1,\mathbf{r}_2)$ is the state-dependent two-body density matrix

$$(2)\quad \rho^{(2)}_n(\mathbf{r}_1,\mathbf{r}_2) = \int \prod_{j=3}^{A} d\mathbf{r}_j\,\psi^*(\mathbf{r}_1,\ldots,\mathbf{r}_A)\,\hat{O}^{(n)}_{12}\,\psi(\mathbf{r}_1,\ldots,\mathbf{r}_A),$$

which we have evaluated within the cluster expansion method with $\psi(\mathbf{r}_1,\ldots,\mathbf{r}_A) = \prod_{i<j}^{A}\hat{f}(r_{ij})\phi(\mathbf{r}_1,\ldots,\mathbf{r}_A)$, ϕ being the independent particle model wave function, and $\hat{O}^{(n)}_{12}$ is the operator

$$(3)\quad \hat{O}^{(n)}_{12} \in \{\hat{1}, \boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2, \hat{S}_{12}\}\otimes\{\hat{1}, \boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2\},$$

acting between particles 1 and 2, present in both the nucleon-nucleon potential and in the ground state wave function. The two-body density appearing in Eq. (1) can be splitted within our approach into the contributions due to proton-proton, proton-neutron and neutron-neutron pairs and the potential energy can thus be splitted into the corresponding contributions. The radial two-body density

$$(4)\quad \rho^{(2)}_n(r_{12}) = \int d\mathbf{R}\,\rho^{(2)}_n\left(\mathbf{r}_1 = \mathbf{R} + \frac{1}{2}\mathbf{r}_{12},\, \mathbf{r}_2 = \mathbf{R} - \frac{1}{2}\mathbf{r}_{12}\right)$$

is shown in Fig. 1 for ^{16}O and ^{40}Ca, for $n = c, \sigma, \tau, \sigma\,\tau, S, S\tau$ in Eqs. (2), (3) and (4).

We have calculated the *pp* and *pn* contributions to potential energy for ^{16}O and ^{40}Ca, using the density of Eq. (2) and the Argonne $AV8'$ potential, obtaining for the following results. The contribution from *central* correlations is small and in this case the probabilities from *pp* and *pn* pairs are exactly proportional to the fractions estimated combinatorically, namely $Z(Z-1)/A(A-1)$ and $2ZN/A(A-1)$, respectively, giving $P(pp) = 23\%$ and $P(pn) = 53\%$ for ^{16}O. In the case of full correlation, this proportionality does not hold anymore, and we find $P(pp) = 8\%$ of the total and $P(pn) = 83\%$ of the total, or $P(I = 0) = 74\%$ and $P(I = 1) = 26\%$, I being the total isospin of the pair. The corresponding calculations for ^{40}Ca give practically the same results.

When simulating the collision of two heavy ions, one starts by constructing some picture of the two involved nuclei, with the positions of the nucleons are sampled according to a density distribution function; this approach completely ignores the structure of the wave function of the nucleus, which is a highly complicated object depending on the positions, momenta, spin and isospin states of A nucleons. In Ref. (8) it was developed a Monte Carlo code to provide a more realistic implementation of the nuclear wave function, including *central* correlations, and providing a good description of two-body densities of the nucleus as compared with the ones obtained within an independent particle model. From this work, we know that basic quantities as the potential energy of the nucleus are strongly affected by realistic SRCs, therefore it appears mandatory to include *state-dependent* correlations in the approach of Ref. (8). To this end, the first improvement to the mentioned approach was to distinguish protons and nucleons, and to implement state-dependent correlations between first-neighbor nucleons. With the newly developed configurations (9) we will be able to investigate various aspects of AA collision (10); Fig. 2 shows the spectator systems after a *Pb-Pb* collision, the NN scattering being treated within the Glauber theory. Correlated nucleons, which will be emitted with high-momentum, are depicted in a different color.

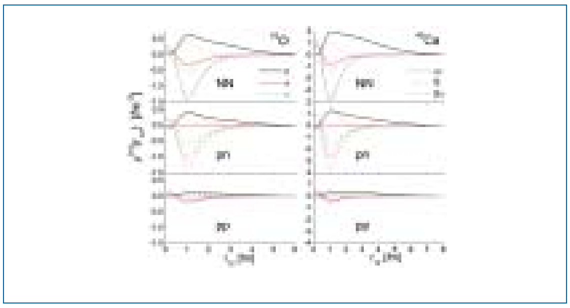

Fig. 1. – The radial, state dependent two-body density matrices (Eq. 4) of ^{16}O (*left column*) and ^{40}Ca (*right column*), as defined in Eq. (2); *Top*: the total Nucleon-Nucleon density; *Center*: the proton-proton density; *Bottom*: the neutron-proton density.

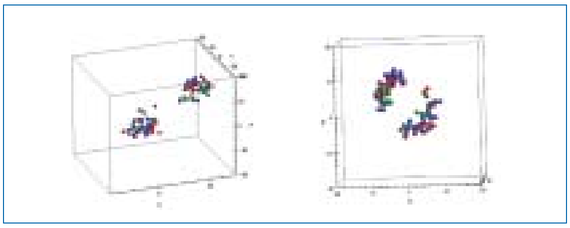

Fig. 2. – The spectator systems after a $Pb - Pb$ collision along the z direction. *Left*: side view; *right*: view from behind. Red and blue spheres are protons and neutron, respectively, while the green ones are those nucleons which belonged to a correlated pair, before the interaction, their correlated partner being among the interacting nucleons (hidden, in this figure). The axes units are in *fm* and the dimension of the spheres are taken as the rms charge radius of the proton; Glauber parameters correspond to RHIC energies. Animations are available (9) along with the configurations used for the colliding nuclei.

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