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The relativistic mean field model proposed by J.D. Walecka was recently used with great success to describe the properties of nuclear matter as well as the structure of the finite static nuclei. Sta ing from Walecka's Lagrangian the nucleons are represented by single particle spinors, which are determined by a Dirac equation contain a repulsive mean neutral vector field V_μ and an attractive mean isoscalar field σ. Both fields satisfy Klein-Gordon equations. Their source terms are again determined by the spinors. We applied this relativistic mean field model to the dynamics of two colliding slabs. They are translational invariant in two transverse dimensions and consist of spin and isospin etric nuclear matter. By specification of appropriate initial conditions for the collision of two equal slabs, we solved the system of coupled Klein-Gordon-Dirac equations for lab bombarding ener s per nucleon up to 400 MeV. At low energies the results are identical with TDHF results. The damping of the collision, the phenomenon of high nuclear density, and the effect of retardation during the reaction are studied.

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To describe a heavy ion collision from the basis of a relativistic quantum field theory is very desirable because in principle one has a complete calculational framework with which to answer any question that can be asked about the system. J.D. Walecka[1)] has proposed a relativistic quantum field theory for nuclear matter that recently was used successfully to determine the structure of finite nuclei.[2-4)] This gives the motivation to extend the Walecka model to describe the dynamics of colliding nuclei.[5)]

To limit the computational scope we consider two colliding equal nuclear slabs of spin and isospin symmetric nuclear matter that are finite in z-direction and infinite in the transverse directions. In the Walecka model, the interaction between the nucleons is due to the exchange of a neutral scalar meson (σ) of mass m_s and a neutral vector meson (V_μ) of mass m_v. The scalar meson couples to the scalar nucleon density through a coupling $-g_s\bar{\psi}\psi\sigma$ and the vector meson to the conserved nucleon current through $ig_v\bar{\psi}\gamma_\lambda\psi V_\lambda$. The field equations become manageable by using the mean field approximation[1)] where one substitutes the meson fields σ and V_μ by their expectation values σ and V_μ and introduces the normal ordering to calculate the expectation values of the source terms. To do so, we assume the relativistic many-body state, which describes the colliding nuclear slabs to be of the form

$$|\phi\rangle = a^+_{\alpha_1} a^+_{\alpha_2} \ldots a^+_{\alpha_A}|0\rangle \tag{1}$$

$a^+_{\alpha_i}$ creates a nucleon characterized by quantum numbers $\alpha \equiv (j, K_\perp)$. j is the z-quantum number and $K_\perp$ the transverse wave number. With this the Euler-Lagrange equations yield Klein-Gordon equations for the mean meson fields and a Dirac equation for the functions $f_{A_{jK_\perp}}$ and $f_{B_{jK_\perp}}$, which correspond to the large and small component of the relativistic single nucleon wave functions.

$$\frac{\partial^2\sigma}{c^2\partial t^2} - \frac{\partial^2\sigma}{\partial z^2} + m_s^2\sigma = -g_s\rho_s \tag{2a}$$

$$\frac{\partial^2 V_o}{c^2\partial t} - \frac{\partial^2 V_o}{\partial z^2} + m_v^2 V_o = g_v\rho_v \tag{2b}$$

$$\frac{\partial^2 V_z}{c^2\partial t} - \frac{\partial^2 V_z}{\partial z} + m_v^2 V_z = g_v j_z \tag{2c}$$

and

$$\frac{\partial}{c\partial t} f_{A_{jK_\perp}} + \left(\frac{\partial}{\partial z} - ig_v V_z\right) f_{B_{jK_\perp}} = i\left(-g_v V_o - \sqrt{K_\perp^2 + m^{*2}}\right) f_{A_{jK_\perp}} \tag{3a}$$

$$\frac{\partial}{c\partial t} f_{B_{jK_\perp}} + \left(\frac{\partial}{\partial z} - ig_v V_z\right) f_{A_{jK_\perp}} = i\left(-g_v V_o + \sqrt{K_\perp^2 + m^{*2}}\right) f_{B_{jK_\perp}} \tag{3b}$$

Here the effective mass is $m^* = m + g_s\sigma$. The scalar density ρ_s, the nucleon density ρ_v, and the nucleon current j_z are determined by the functions f_A and f_B.

$$\rho_s = \frac{2}{\pi} \sum_j \int dK_\perp K_\perp \frac{m^*}{\sqrt{K_\perp^2 + m^{*2}}} \left\{ |f_A|^2 - |f_B|^2 \right\} \tag{4a}$$

$$\rho_v = \frac{2}{\pi} \sum_j \int dK_\perp K_\perp \left\{ |f_A|^2 + |f_B|^2 \right\} \tag{4a}$$

$$j_z = \frac{2}{\pi} \sum_j \int dK_\perp K_\perp \left\{ f_A^* f_B + f_B^* f_A \right\} \tag{4b}$$

The appropriate initial condition for the approaching slabs is constructed by an inhomogeneous Lorentz transformation applied to the static relativistic nucleon wave functions, which correspond to the ground state of a single slab at rest.

The half-side momentum per area unit

$$\frac{P_z}{F} = \frac{1}{c} \int dz \left\{ \langle\phi|\psi^+ \frac{\partial}{i\partial z} \psi|\phi\rangle - \frac{\partial\sigma}{c\partial t} \frac{\partial\sigma}{\partial z} - \frac{\partial V_z}{\partial z}\left(\frac{\partial V_0}{\partial z} + \frac{\partial V_z}{c\partial t}\right)\right\} \qquad (5)$$

determines the amount of energy that is transferred during the reaction from initial kinetic energy to intrinsic excitation.

We solved the coupled system of differential equations (2),(3) numerically for different bombarding energies. Initially, each slab is in its ground state. With the constraint of 1.4 nucleons per unit area for each slab, self-consistency leads to a slab built up by four relativistic single nucleon wave functions. The slab thickness corresponds to a nucleus of A = 35. Since the functions $f_{A/B}$ depend weakly on $K_\perp$, we consider in our computation only wave functions with $K_\perp = 0$. At energies lower than $E_{c.m.}/A = 100$ MeV, we neglect the second time-derivations in the Klein-Gordon equations (2); that means, we neglect retardation effects.

Figure 1 shows the resulting density ρ_V during the slab collision at the low energy of $E_{c.m.}/A = 3.5$ MeV. The time t is in units of 10^{-21} sec. After the collision about 70% of the initial energy is transferred into intrinsic excitation. These results are almost identical with the corresponding TDHF calculations[6]. At the intermediate energy of $E_{c.m.}/A = 25$ MeV, the profiles for ρ_V are shown in Fig. 2. While at this energy the TDHF model predicts several lumps of nuclear matter to appear at the surface which separate off, here a neck of matter between two big separating fragments is formed. Finally, the neck contracts, forming two clusters.

Figure 3 displays the density profiles at the high bombarding energy of $E_{c.m.}/A = 100$ MeV. The maximum density reached is less than $2\rho_0$. The dashed curves in Fig. 3 show the results taking the second time-derivations in Eqs. (2) into account. Obviously, retardation smooths the density profiles. Finally, Fig. 4 displays the meson fields at three different times during the slab collision. During the stage of initial penetration the vector field becomes very strong, slowing down the colliding slabs.[7)]

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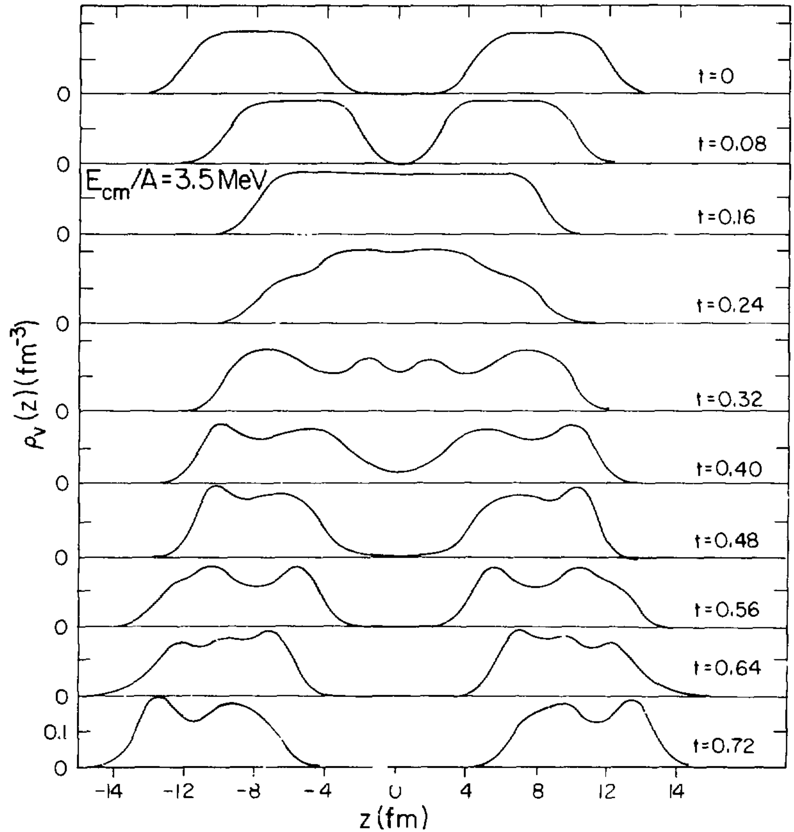

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Fig. 1

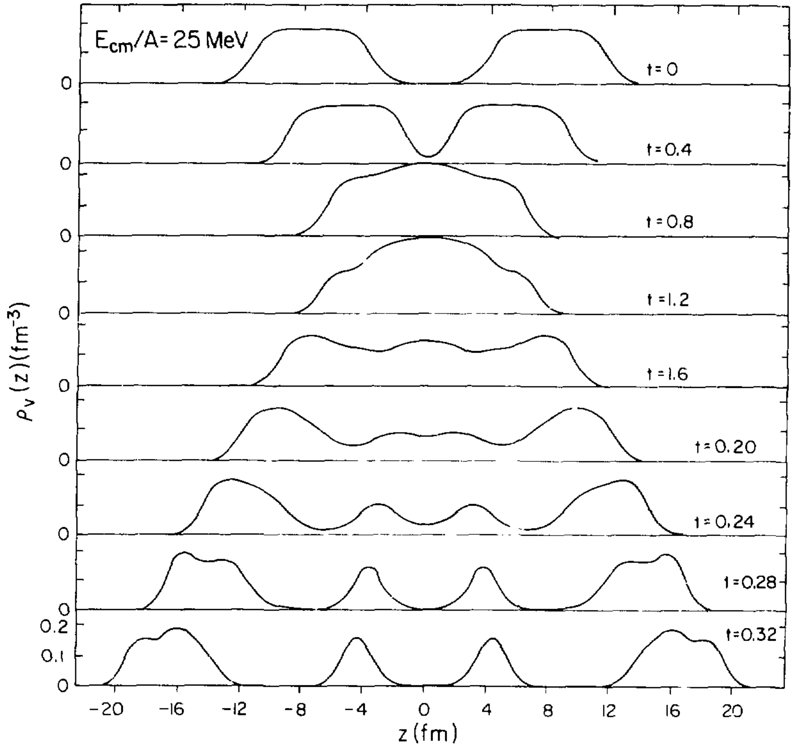

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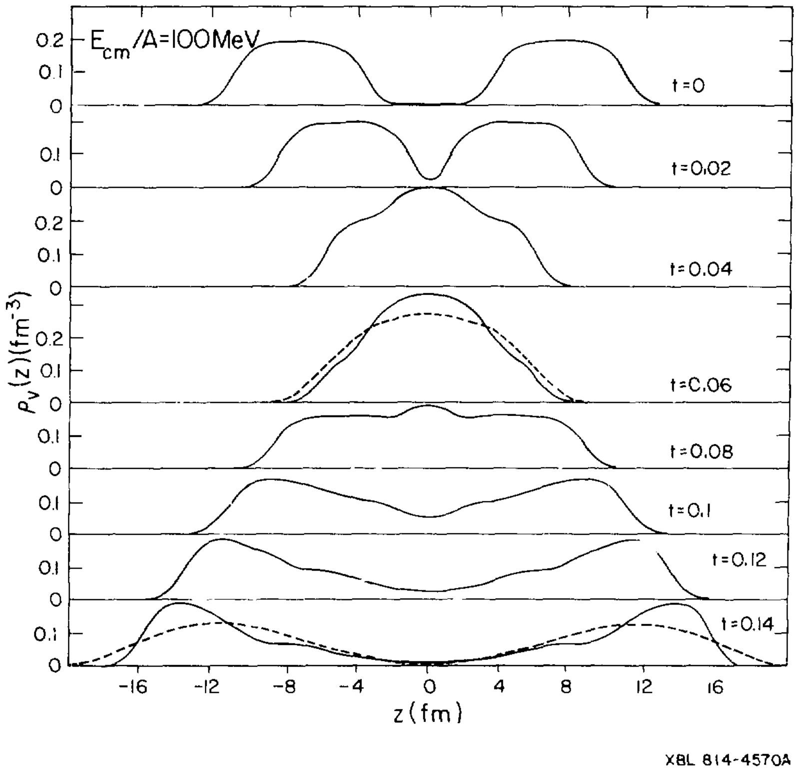
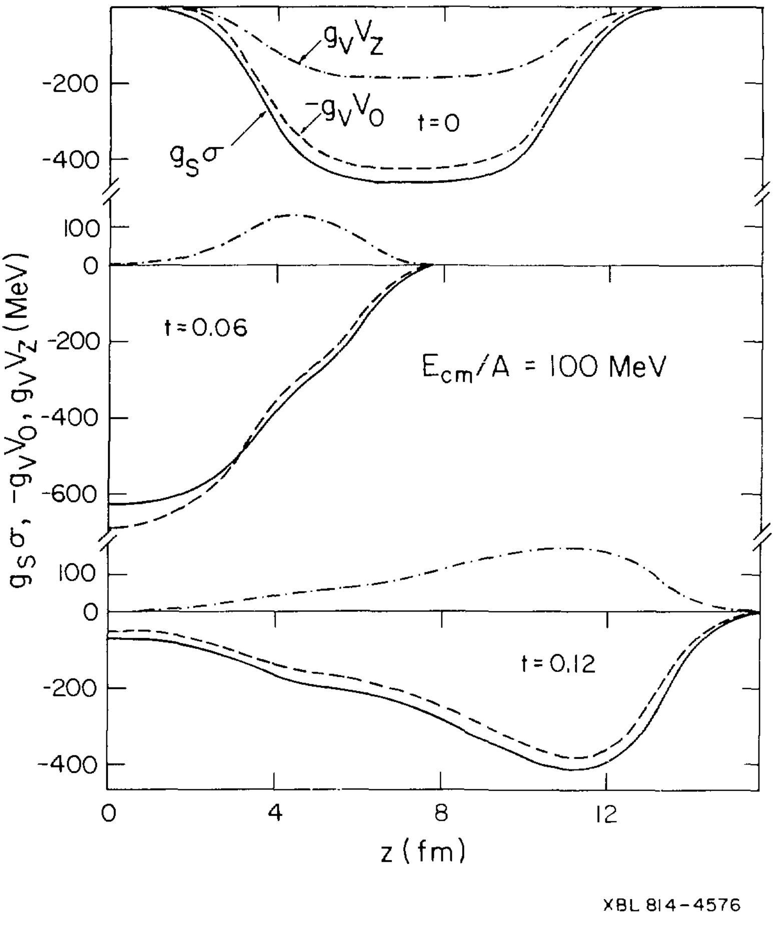
Fig. 2



E_cm/A=100MeV
t=0
t=0.02
t=0.04
t=0.06
t=0.08
t=0.1
t=0.12
t=0.14
ρ_v(z)(fm^-3)
z(fm)
XBL 814-4570A

Fig. 3



$g_V V_Z$
$-g_V V_0$
$g_S \sigma$
t=0
t=0.06
t=0.12
E_{cm}/A = 100 MeV
$g_S\sigma$, $-g_V V_0$, $g_V V_Z$ (MeV)
z (fm)
XBL 814-4576

Fig. 4