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**A TIME-DEPENDENT MEAN-FIELD THEORY FOR PROMPT NUCLEON EMISSION
IN HEAVY-ION REACTIONS**

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A TIME-DEPENDENT MEAN-FIELD THEORY FOR PROMPT NUCLEON EMISSION IN HEAVY-ION REACTIONS*

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In recent years the study of fast particles emitted during heavy-ion reactions has been one of the outstanding problems of nuclear physics. Here we present a mean-field theory for the problem.¹ The essence of the model is to treat the relative motion of the ions classically while treating the internal excitations quantum mechanically. The motivation for the theory comes from the earlier time-dependent Hartree-Fock (TDHF) calculations.² These calculations have shown that the time scale for particle emission was on the order of 10^{-22} secs., and, in particular, these particles were emitted before dynamical rearrangement and exchange processes induce an appreciable change on the entrance channel values of the heavy-ion masses and energies. We consider particle emission from a reaction of the type $A+B \rightarrow N+X$, where N denotes a single emitted nucleon and X stands for everything else. Here, for simplicity, we study particle emission from fragment A which is perturbed by the external time-dependent field produced by a structureless particle of mass B located at a distance R from the center of A . The Hamiltonian which governs the system can be written as

$$H(\{\vec{r}_i\}, \vec{R}) = H_0(\{\vec{r}_i\}) + T_{\vec{R}} + U(\vec{R}, \{\vec{r}_i\})$$

where H is the intrinsic Hartree-Fock Hamiltonian for A , depending on the intrinsic coordinates $\{\vec{r}_i\}$. T is the relative kinetic energy of A and B , and U is an external one-body field which induces the coupling between the internal degrees of freedom of A and the relative motion of B

$$U(\vec{R}, \{\vec{r}_i\}) = \sum u(\vec{r}_i - \vec{R}).$$

The one-body nature of U is an assumption of our model. We approximate the wavefunction Ψ associated with H to be a product of two terms,

$$\Psi(\{\vec{r}_i\}, \vec{R}, t) = G(\vec{R}, t) \Phi(\{\vec{r}_i\}, t)$$

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where ϕ is a time-dependent Slater determinant of single-particle states ϕ_λ describing the motion of the particles in A, and G is the wavefunction which gives the motion of B. Variation of the action with respect to G^* and ϕ_λ^* yields the dynamical equations for ϕ_λ

$$[h(\vec{r}, t) + \int d\vec{R} |G(\vec{R}, t)|^2 u(\vec{r}-\vec{R}) - i\hbar\partial_t] \phi_\lambda(\vec{r}, t) = 0 \quad (1)$$

and for G

$$[T_{\vec{R}} + \int d\vec{r} \rho(\vec{r}, t) u(\vec{r}-\vec{R}) - i\hbar\partial_t] G(\vec{R}, t) = 0. \quad (2)$$

Here h and ρ are the single-particle Hartree-Fock Hamiltonian and the single-particle density for A. The solution of Eq. (2) is obtained, in the classical limit, by using wavepackets which are localized on classical trajectories. We also calculate one- and two-particle inclusive, invariant cross sections as³

$$\frac{d^3\sigma(1)}{dk^3} = \frac{1}{(2\pi)^2} \sum_{\lambda=1}^A \int_0^{b_{\max}} b db |C_{\vec{k}\lambda}(\infty)|^2 \quad (3a)$$

$$\frac{d^6\sigma(2)}{d^3kd^3q} = \frac{1}{(2\pi)^5} \int_0^{b_{\max}} db b \left\{ \sum_{\lambda, \mu=1}^A |C_{\vec{k}\lambda}|^2 |C_{\vec{q}\mu}|^2 - \left| \sum_{\lambda=1}^A C_{\vec{k}\lambda}^* C_{\vec{q}\lambda} \right|^2 \right\}. \quad (3b)$$

In the above expressions, b denotes the impact parameter, and the C variables are the expansion coefficients of ϕ_λ in terms of the bound and continuum states⁴ of h_0 , which measure the occupation-probability transfer from bound to continuum states. For these calculations, we have used a phenomenological external field which was a rank-one, separable potential. For the deep-inelastic branch of the $^{160}\text{Pb} + ^{93}\text{Nb}$ reaction at $E_{\text{lab}} = 204$ MeV the range was adjusted so as to contain the interaction within the strong absorption radius of this system, and the adjustment of the strength gave us a multiplicity of 0.134 in agreement with the corresponding experimental value.⁵ The s-wave contribution from ^{160}Pb to the following results is less than 1% in agreement with the previous TDHF result. We have used a Coulomb trajectory generated by a modified Coulomb potential. We calculate the mean velocity of the frame from which the neutrons are emitted as

$$V_b = \int_{-\infty}^{+\infty} dt p(t) V_T(t) / \int_{-\infty}^{+\infty} dt p(t)$$

where V_T is the relative velocity of the ions on the trajectory, and $p(t)$ is the total emission probability in time. The average of V_b over all trajectories yields a moving source velocity of $0.124c$. In Fig. 1 we show the contours of the invariant singles cross section as a function of longitudinal and transverse velocities. From this figure we can deduce the following observations: The contours are centered around the moving source velocity, and they have the characteristic exponential dependence on the total velocity. The energy-angle cross sections are shown in Fig. 2 as a function of energy and angle. The experimental results are also shown, and we see a fairly good agreement with the data except at 63° . This disagreement may be

Fig. 1. Contours of the invariant cross section as a function of transverse and longitudinal velocities.

Fig. 2. Double differential cross sections as a function of laboratory energy for angles 14°, 24°, and 63°.

due to the exclusion of the emission from Nb in our calculations. In order to extract a temperature parameter, we have fitted the angle integrated energy spectrum to the functional form

$$\frac{d\sigma}{d\epsilon} \cong N \left(\frac{\epsilon}{T} \right)^\alpha e^{-\epsilon/T}$$

with $N = 69.3 \text{ fm}^2 \text{ MeV}$, $T = 5.2 \text{ MeV}$, and $\alpha = 1.32$. In Fig. 3 we show the two-particle cross section of Eq. (3b) as a function of the relative two-neutron velocity. Since we have derived a mean-field theory, it is important to understand the source of these correlations. First, the wavefunction of the nucleus is at all times a Slater determinant. The antisymmetry of the wavefunction leads to the second term on the righthand side of Eq. (3b). The second type of correlations are the dynamical correlations. There is yet another source of correlations which is not in our model. If two nucleons are emitted in nearly the same direction, then they will interact substantially before they reach the detector. Since this interaction will be dominated by the deuteron pole, we have used the separable interaction of Yamaguchi⁶ as our residual interaction. The dashed line of Fig. 3 shows the effect of this final-state interaction upon the two-neutron cross section. As we see, the effect of a residual interaction leaves the momentum localization unchanged. The naive application of the uncertainty relation gives us an equivalent space localization of 2.5 fm which is approximately the size of ¹⁶⁰. These results show the similar characteristics of

two-particle correlations obtained for other systems.^{7,8}

Fig. 3. Two-neutron cross section of Eq. (3b) as a function of relative neutron momentum (solid line) and the same curve with the addition of a final-state interaction (dashed curve). The dashed curve is divided by 100.

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