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Rapport Interne LPN - 90-10

UNIVERSITE DE NANTES

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Abstract :

Calculations were carried out within the Landau Vlasov model formalism, using an effective force which has an adjustable isospin dependent term. We showed that the strength of this term is influencing the dynamics of heavy-ions collisions ; at relatively high energy, nuclear preequilibrium fluxes are sensitive to the isospin strength.

Introduction

Heavy-ion physics with radioactive beams open new domains of research where properties of nuclei very far from the beta stability line can be explored. Such secondary beams become available with sufficient energy and intensity so that collisions between nuclei with very unbalanced isospin degrees of freedom are now possible. The main experimental and theoretical outputs may be expected in spectroscopic and radioactive properties of very proton rich (poor) nuclei ; however, in this paper, we report on a preliminary investigation on the effects that isospin relaxation could induce on the reaction dynamics itself.

In previous works, microscopic studies of heavy-ion peripheral reactions /1/ and of giant resonances excited during collisions /2/ have shown the ability of semi-classical models, as the Landau-Vlasov model /3/, to describe with a good precision monopole scalar and dipole isoscalar resonances ; energies of those resonances are generally in good agreement with experimental results and with microscopic quantum theory ; widths are however generally underestimated, particularly close to equilibrium, due to the neglect of the so-called quantum escape /2/. However, at high excitation energies such source of spreading becomes less important ; we then feel confident in the ability of the Landau Vlasov model to describe the dynamics of nucleons fluxes generated by the processes of isospin equilibration.

We focus ourselves on the isospin degree of freedom since it has been recognized for one or two decades as one of the fastest collective degree of freedom, we then expect that tracks of its equilibration may survive in sufficiently energetic reactions, even if the high rates of evaporation progressively wash out its signature in the N/Z ratios of the detected fragments /4/.

In the following, we shall briefly sketch out the formalism and the inclusion of an isospin dependent component in the effective nuclear interaction. In this report, we aim at answering two related questions :

(i) What are the effects of the isospin dependent component of the interaction on dynamics of reactions described within Landau-Vlasov formalism ?

(ii) Are there sizeable differences in dynamics of reactions induced by radioactive beams in comparison with reactions induced by comparable beams close to the beta stability line ?

We present results of two sets of calculations : one at relatively low energy, particularly for peripheral collisions, where N/Z equilibration is well established, to check the sensitivity of the model to the introduction of an isospin dependent component of the force ; the other at higher energies, in central collisions, close to the limit of fusion processes, to study in particular the structure of the fast emission of particles.

II - Landau-Vlasov with an isospin dependent interaction

Calculations are made within the so-called Landau-Vlasov model of heavy-ion reactions ; this model distinguishes itself from other transport equations -based on Vlasov equation for the mean field and Uehling-Uhlenbeck collision term- by the use of a continuous basis of coherent (gaussian) states to project the one-body density. Detailed description of the model can be found elsewhere (e.g. see /3/), but note that a gaussian basis allows accurate descriptions of the diffuse part of the nuclear surface and is stable enough to describe bulk properties of nuclei at (or close to) equilibrium.

In the present work, we introduced in the usual effective force an extra term which is isospin dependent. The potential energy density reads,

$$E(\rho, \xi) = \frac{\tau_0}{2} \rho^2 + \frac{\tau_3}{2 + \nu} \rho^2 + \nu + c \frac{\xi^2 \rho}{\rho_\infty^2} \quad (1)$$

$$\rho = \rho_n + \rho_p$$

$$\xi = \rho_n - \rho_p$$

and ρ_∞ the saturation density of infinite nuclear matter.

For the first two terms we used Zamick parametrization

$$\tau_0 = - 356 \text{ MeV. } \rho_0^{-1}$$

$$\tau_3 = 303 \text{ MeV. } \rho_0^{-7/6}$$

$$\nu = 1/6$$

This simplified form for the isospin dependent term fits particularly well the formalism used in Landau-Vlasov model. The parameter c can be related, in the limit of infinite nuclear matter, to the volume-symmetry coefficient J of mass formula

$$J = c + \frac{h^2}{6M} k_F^2 \quad (2)$$

k_F is the Fermi momentum of infinite nuclear matter.

In this study c is used as a free parameter to enhance the effects we are looking for ; calculations have been carried out for $c = 0$ (standard Zamick force), $c = 20$ and $c = 28$ corresponding respectively to $J = 31.5$ and 39.5 MeV, values compatible with those extracted from mass formulae /5/ (and references quoted therein). The one-body potential then reads,

$$U_q(\rho, \xi) = \tau_0 \rho + \tau_3 \rho^1 + \nu + c \xi^2 + 4 c \frac{q \rho \xi}{\rho_\infty^2} \quad (3)$$

where $q = 1/2$ (respect. $-1/2$) for neutrons (respect. protons).

Binding energies of some Ca isotopes calculated for different values of c are shown in fig.1. As expected, nuclei become less and less bound with an increasing c ; the gain in energy for each nucleon is proportional to $J.I^2$ ($I = (N-Z)/A$), most dramatic changes are then for isotope ^{56}Ca . The theoretical results tend to overbind the nuclei, this is connected with the simplified character of the local density energy of eq.1.

Fig. 1
Binding energies of some Ca isotopes for different values of c . Experimental values for ^{40}Ca and ^{48}Ca are from ref.9. The value for ^{56}Ca is from an ETFSI calculation of J.M. Pearson (Univ. de MONTREAL).

Fig.2
Fermi energies of some Ca isotopes for different values of c . Experimental values are from ref.9.

Fig.2 shows Fermi energies for neutrons and protons for the same Ca isotopes. Note that for $c = 0$ neutrons are more bound than protons for ^{48}Ca contrarily to experimental values /6/. For $c = 20$ and $c = 28$ we have a correct global description of Fermi energies, showing that the model is accurate enough to be sensible to isospin effects. We did not try a precise fitting to experimental data for binding energies and Fermi energies, which could have been in principle possible with a fine tuning of the gaussian width. Previous results show that the treatment of the isospin dependent term is accurate enough in the Landau-Vlasov model to let us hope to get information in dynamical calculations.

III - Peripheral collisions at 15 MeV/u

We investigated peripheral collisions between various Ca isotopes at 15 MeV/u incident kinetic energy with an impact parameter $b = 7$ fm ;

Table I

Value of $N - Z$ for the quasi target (Q.T) and the quasi-projectile (Q.P) created during the collision of Ca isotopes at impact parameter $b = 7$ fm.

		N - Z		
		c = 0	c = 20	c = 28
$^{56}\text{Ca}(15 \text{ MeV/u}) + ^{40}\text{Ca}$	Q.T	3.74	4.64	5.02
	Q.P	8.76	5.82	4.92
$^{48}\text{Ca}(15 \text{ MeV/u}) + ^{48}\text{Ca}$	Q.T	6.52	5.78	5.52
	Q.P	6.96	5.84	5.12

Table I presents results for the N/Z equilibration observed for the 3 values of c in two different collisions $^{56}\text{Ca}(15 \text{ MeV/u}) + ^{40}\text{Ca}$ and $^{48}\text{Ca}(15 \text{ MeV/u}) + ^{48}\text{Ca}$. In both reactions the total mass number and charge number are the same. Recall that initial values for the asymmetric system of $(N-Z)$ are respectively 0 (16) for the target (projectile). The switch on of the isospin interaction is needed to achieve complete equilibration. The results for the symmetric system are to give an estimate of the numerical fluctuations which arise from the stochastic treatment of $n-n$ collisions.

A tentative explanation for the role of isospin in equilibration could be the following : it was suggested /7/ that the large value of the neutron-proton scattering cross section at low energy in comparison with the neutron-neutron or proton-proton scattering cross sections favor a proton deficit of the light collision partner ; on the other hand it is well known that increasing c in the interaction, which is tantamount to increasing J , favors the formation of a neutron skin in the nuclei /8/. Therefore as c increases there will be more and more neutron-neutron collisions and this will compensate for the lower cross section.

Fig. 3
Influence of the isospin on the dynamics of the reaction ^{56}Ca (15 MeV/u) + ^{40}Ca at $b = 7\text{ fm}$.

Influence of the isospin on the dynamics can also be seen in Fig. 3 which shows plot of the density of matter at 2 times : $t = 160$ and $t = 240\text{ fm/c}$ for the ^{56}Ca (15 MeV/u) + ^{40}Ca for the 3 values of c . The reaction time clearly depends on. The effect on the neck formation is also sensitive this could be significant for mass exchanges and the overall reaction dynamics.

IV - Central collisions

In order to study the isospin effects at higher energies, we carried out calculations central on collisions ($b = 2\text{ fm}$) with the same Ca isotopes at 40 MeV/u incident kinetic energy. We select central collisions to analyze the preequilibrium emissions which could be sensitive to variations of the initial value isospin of the interacting ions.

For the isospin interaction strength $c = 20\text{ MeV}$, the ^{48}Ca (40 MeV/u) + ^{48}Ca does not fuse and yields a quasi-fragmentation process, whereas the ^{56}Ca (40 MeV/u) + ^{40}Ca leads to fusion. This difference is noticeable even if the latter system has a little less available energy in the mass center (942 MeV versus 960 MeV for the former system).

We analyze the emitted particle flux through a sphere, centered at the c.m. of the system, large enough (13 fm radius) to contain the main fragments of the compound nucleus, at least until $t = 200$ fm/c. In fig. 4a are shown the numbers of emitted protons and nucleons during the collision, for various values of isospin strength c . The switch on of the isospin interaction increases the emitted flux slightly, this increase being mostly due to neutrons ; the number of protons being unsensitive to isospin strength in the equilibrated system $^{48}\text{Ca} + ^{48}\text{Ca}$.

Fig. 4a

Number of emitted protons and neutrons during the collision ^{48}Ca (40 MeV/u) + ^{48}Ca for different values of c .

Fig. 4b

Number of emitted protons and neutrons during the collisions ^{48}Ca (40 MeV/u) + ^{48}Ca and ^{56}Ca (40MeV/u) + ^{40}Ca for $c = 20$

The total flux, fig. 4b (shown here for $c = 20$ MeV) is 7% more intense for the isospin unbalanced system ; than for the balanced one. This increase is created at the beginning of the reaction (around 120 fm/c) ; this is understandable since both systems have the same compound limit, the latter stages of particle emissions are similar.

To go further in the analysis, we look at the instantaneous value of the $I = (N-Z)/A$ coefficient of the emitted fluxes (Fig. 5a, 5b). As expected, we have a net dependence of the time-evolution of I on the value of c ; with large initial fluctuations due to the small number of nucleons taken into account. With c growing, neutrons are less bound which favors an increase of I . Note that the asymptotic values of I are quickly reached, the I coefficient is fixed at around 140 fm/c. For a given value of c , equilibration is faster for the reaction $^{56}\text{Ca} + ^{40}\text{Ca}$, because the two nuclei have very different Z/A ratios, so that the isospin mode could be initially more excited. At least, for the higher value of c (28 MeV), both systems have the same asymptotic $(N-Z)/A$ ratio; for $c = 20$ MeV, this ratio for the $^{48}\text{Ca} + ^{48}\text{Ca}$ system is 20 % lower than that the $^{56}\text{Ca} + ^{40}\text{Ca}$ system.

Fig. 5a
Time evolution of $I = N-Z/A$ for different values of c during the reaction ^{48}Ca (40 MeV) + ^{48}Ca .

Fig. 5b
Time evolution of $I = N-Z/A$ for the reactions $^{48}\text{Ca}(40 \text{ MeV/u}) + ^{48}\text{Ca}$ and $^{56}\text{Ca}(40 \text{ MeV/u}) + ^{40}\text{Ca}$ for $c = 20$

Conclusions

In this preliminary report, we have shown that the semi-classical kinetic equations can be used to study the effects of the isospin degree of freedom on nuclear reactions. On top of numerical fluctuations, intrinsically generated by the solution method, clear signals of charge exchange effects on dynamics can be seen ; they could be experimentally observed in the transition energy zones, where reaction regimes change. In particular, at high energies, the dependence of nuclear preequilibrium fluxes on the isospin balance between the two interacting ions, affects significantly the linear momentum transfer.

Such calculations, also show that semi-classical models can be used to study microscopically nuclear fluxes between interacting ions and then to study the mechanisms of energy equilibration in deep inelastic reactions.

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