UNIVERSIDADE DE SÃO PAULO

publicações

INSTITUTO DE FÍSICA
CAIXA POSTAL 20516
01498 - SÃO PAULO - SP
BRASIL

IFUSP/P-551

THE STATISTICAL "DOORWAY" ROLE OF THE DINUCLEUS IN HEAVY ION DEEP INELASTIC REACTIONS

by

R. Bonetti

Istituto di Fìsica Generale Applicata
Università degli Studi di Milano
Via Celoria, 16 - Milano, Italy

and

M.S. Hussein

Instituto de Física, Universidade de São Paulo

Outubro/1985

THE STATISTICAL "DOORWAY" ROLE OF THE DINUCLEUS IN HEAVY ION DEEP INELASTIC REACTIONS*

R. BONETTI
Istituto di Fìsica Generale Applicata - Università degli Studi
di Milano - Via Celoria, 16
Milano, Italy

and

M.S. HUSSEIN
Instituto de Física da Universidade de São Paulo - C.P. 20516
São Paulo, SP, BRASIL

October/1985

ABSTRACT

The statistical role of the dinucleus as a "doorway" in heavy-ion deep inelastic reactions is discussed. A detailed analysis of the reactions $^{28}Si + ^{64}Ni$ at $120 < E_C < 126.75$ MeV and $^{12}C + ^{24}Mg$ at $30 < E_{CM} < 42$ MeV is presented. It is pointed out that the life-time of the dinucleus extracted from Ericson - type analysis is close to that extracted from the final fragment angular and charge distributions.

---

* Supported in part by FAPESP and CNPq (Brazilian Agency) and the INFN, Sezione, Milano

It is by now clear that deep inelastic heavy ion reactions are statistical processes that are characterized by a time delay intermediate between direct and compound nuclear reactions. This is evidenced by non-equilibrated exit channel mass distributions (peaking around the projectile mass), and, on the other hand, by the complete damping of the energy and angular momentum of relative motion. In very heavy ion systems, one usually employs the classifcal deflection functions to obtain the correlation of energy loss with average deflection angle, through which one extracts the reaction times ($\sim 10^{-21}$s).

In light heavy-ion systems, the strong Coulomb focussing commonly seen in heavier system is missing. In fact, here, one encounters an orbiting type angular distribution going like $\frac{d\sigma}{d\Omega} \propto \frac{1}{\sin\theta}$ at larger angles, resembling very much compound nucleus angular distributions[2)]. This fact is consistent with the idea that a rather long-lived dinucleus is formed in the initial stage of the reaction, which would act as a "doorway" to DIC.

So far, however, evidence in favor of the idea of the dinucleus has been indirect, and only recently, attempts were made to actually study the statistical consequences of it presence through an Ericson type analysis of the DIC excitation fucntions[3,4)]. Further, the recent global analysis of heavy-ion fusion reactions done by Hussein et al.[5)], also clearly indicated the important role of the dinucleus as a

"doorway". Therefore one reaches the conclusion, that a consistent picture of both DIC and fusion does emerge if one considers explicitly the dinucleus as a common doorway. At a more microscopic level, one of course would view the dinucleus as a kind of geometrical realization of overlapping, doorway configurations.

In the Ericson fluctuaction analysis reported in Ref. 3 and Ref. 4 one obtains the average width and the lifetime of these doorway configurations. To what extent this lifetime is identifiable with the usual extraction of lifetime from the final fragment change and angular distribution? It is the aim of this paper to present a comparison of these lifetimes for the systems studied in Refs. 3 and 4. Further, we attempt to answer the question of how to formulate a theory of a hybrid, nuclear reactions that leads to fluctuating excitation functions (reminiscent of compound processes) and forward, grazing, peaked angular distribution.

We first consider the reaction, ^{28}Si + ^{64}Ni, in the laboratory energy range $120 < E_{Lab} < 126.75$ Mev, studied recently by De Rosa et al.[3)]. These authors measured the DIC excitation function, corresponding to a Q-value bin of about 25 MeV. Normally, one expects, in such an inclusive measurement, to wash out all statistical Ericson-type fluctuations (since the magnitude of the oscillations goes like N_{eff}^{-1}, with N_{eff} being the effective number of channels expected to couple to the source of these fluctuations). However, if a dinucleus is formed with a lifetime shorter than that of the compound nucleus and which acts like a doorway to DIC, one may see its remnant in the form of over-all modulations in the inclusive cross-section excitation function.

We show in Fig. 1 the extracted dinucleus lifetime, from the Ericson-type analysis that employs the spectral density method[6], for different projectile like fragment charges ($10 < Z_f < 16$). Also indicated in the figure, are the nuclear passagem time ($\approx 0.4 \times 10^{-21}$ sec.) and the compound nucleus time delay (if it were formed), $\approx 6.6 \times 10^{-21}$ sec.. One therefore see clearly that the fluctuations in the DIC excitation function correspond to a class of overlapping resonance intermediate in complexity.

The above discussion is based on the entrance channel effect on DIC (through the incident energies). It is important to test the consequences of the formation of the dinucleus on the final channels charge and angular distribution.

We present in Fig. 2 the measured charge distributions for several center of mass angles. The figure shows the usual feature of a gradual broadening of the charge distribution with increasing angle away from the grazing one. In fact, it is easy to verify the diffusion nature of the charge equilibration by looking at the variation of the square of the width at half maximum of the charge distributions as a function of angle (or

equivalently reaction time). This is shown in Fig. 3.

It is of importance at this point to develop a model which exhibits both statistical fluctuations in the entrance channel as well as some kind of focussing in the angular distributions of outgoing fragments. This implies that phases of the S-matrix elements are not completely random: the average of products such as $< S_\ell^* , S_\ell >$ is not zero for several values of unequal ℓ and ℓ' (see below).

Several papers have addressed the question of partial coherence (or partial statisticality) in heavy-ion reactions[8,9]. These authors, however, have looked only at the energy averaged angular distributions. Here, we attempt to extend the discussion to include also the excitation function and the corresponding cross section correlation function.

Let us indicate by S_ℓ, the partial wave S-matrix element relevant to our DIC problem. It seems plausible to assume that the energy average of S_ℓ is zero, consistent with the statistical nature of the reaction under consideration. The second moment of S_ℓ, $<S_\ell^*,S_\ell>$ is $<S_\ell^*,S_\ell> = F(\ell,\ell')e^{i(\delta_\ell,\delta_{\ell'})}$ where $F(\ell,\ell')$ represents the degree of coherence among the partial waves; $F(\ell,\ell') \propto \delta_{\ell\ell'}$, for a pure incoherent compound processes, while it has a finite distribution in $\ell-\ell'$ for the more coherent DIC under consideration.

What interests us here is the S-matrix correlation function defined by

$$C^{(s)}_{\ell,\ell'}(\varepsilon) = \left\langle S^{*}_{\ell'}(E)\, S_{\ell}(E+\varepsilon)\right\rangle \qquad (1)$$

If S is dominated by the dinucleus resonances, these will appear as poles. A possible form for C, which maintains the feature of partial coherence, is

$$C^{(s)}_{\ell,\ell'}(\varepsilon) = \frac{\langle X\rangle\langle X\rangle}{1+i\varepsilon/\Gamma_{corr.}} \cdot \exp\left[-(\ell-\ell')^2/2\lambda_c^2\right]$$

$$\times \exp\left[i(\ell-\ell')\langle\theta_{\ell_0}\rangle\right] \qquad (2)$$

where Γ is the coherence width inversely proportional to the dinucleus lifetime, λ_c the correlation length which measures the number of interfering partial waves, and $<\theta_{\ell_0}>$ is the average deflection function. The <X><X> factor is directly related to the partial cross section[10]. The expression given above results in an average cross section correlation function which is practically angle independent. Further the average cross section would still present the usual characteristics of focussing.

The degree of focussing, and thus the deviation from a pure statistical behaviour (symmetry about 90°), of the average cross section can be assessed through a knowledge of the correlation length, λ_c. One can establish the following relation between the correlation width of the dinucleus, Γ_{corr}, and λ_c 8).

$$\lambda_{corr} = \left(\frac{2\mathcal{J}_d}{\hbar^2 c^2 \delta}\right) \Gamma_{corr.} \qquad (3)$$

where $\mathcal{J}_d$ is the moment of inertia of the dinucleus[5]

$$\mathcal{J}_d = \frac{2}{5} A_1 R_1^2 + \frac{2}{5} A_2 R_2^2 + \mu (R_1+R_2)^2 \qquad (4),$$

and δ measures the angular dispersion extent of the wave packet describing the system at the moment of contact8). It is of the order of few units of $\hbar$ (if measured in these units). Using for the radius parameter the value r_0 = 1.2fm, we obtain for the moment of inertia of the dinucleus in ^{28}Si + ^{64}Ni, the value $\mathcal{J}_d$ = 2127.3 mc^2 [MeVfm^2] where m is the nucleon mass. We thus have

$$\lambda_{corr} \simeq \left(\frac{102}{\delta}\right) \Gamma_{corr} \simeq 10\, \Gamma_{corr.}/\mathrm{Mev} \qquad (5)$$

For the range of values of Γ_{corr} reported by De Rossa[3] namely $200 < \Gamma_{corr} < 800$ keV, shown in Fig. as h/Γ_{corr}, we obtain the corresponding range of values of λ_{corr}, $2 < \lambda_{corr} < 8$. Thus the number of interfering partial waves range between 2 for fragments charge several units away from the projectile, and 8 for projectile-like fragments. This is quite consistent with the measured angular distributions of these fragments: grazing angle peaked for projectile-like fragments indicative of a rather strong focussing resulting from a larger number of interfering partial waves, compared to a very broad distribution for other fragments.

For the lighter systems, such as the one studied by Glaesner et al.[4] ($^{12}C + ^{24}Mg$), we obtain $\mathcal{I}_d = 200.86 (mc^2)$ MeVfm^2 which gives

$$\lambda_{corr.} = \left(\frac{9.63}{\delta}\right) \Gamma_{corr.} \simeq \frac{\Gamma_{corr.}}{Mev.} \qquad (6)$$

with the Γ_{corr} value obtained in Ref. 4) namely 0.24 MeV, we get $\lambda_{corr} < 1$. This is clearly consistent with the type of angular distribution of DIC products reported by Glaesner et al.[4], namely completely isotropic resembling very much a process occuring through the compound nucleus (no interference).

In conclusion, we have shown that the time delay of deeply inelastic reactions extracted from final fragment distributions (angle, charge tc.), is consistent with that deduced from the entrance channel energy fluctuations. This clearly demonstrates the "doorway" rôle of the dinucleus formed in the initial stage of the reaction. A simple relation between the number of interfering partial waves, exemplified by the correlation length λ_{corr} and the correlation width Γ_{corr} extracted from Ericson analysis of DIC excitation functio has been established.

It would be extremely interesting to extend these findings to very heavy systems through detailed measurements of the energy dependence of the DIC cross section.

REFERENCES:

1) W.U. Schröder and J.R. Huizenga, Ann. Rev. Nucl. Sci. 27 (1977) 465.

2) D. Shapira et al., Phys. Rev. Lett. 43 (1979) 1781; Phys. Rev. C21 (1980) 1824.

3) A. De Rossa, G. Inglima, V. Russo, M. Sandoli, G. Fortuna, G. Montagnoli, C. Signorini, A.M. Stefanini, G. Cardella, G. Pappalardo and F. Rizzo, Phys. Lett. 160B (1985) 239

M. Sandoli, Proceedings of the International Conference on Nuclear Structure and Heavy Ion Reactions, Legnaro, Padova. May 1985, to be published;

G. Pappalardo, Proceedings of the International Conference on Reaction Mechanisms, Varenna, Italy. June 1985, to be published.

4) A. Glaesner, W. Dünnweber, W. Hering, D. Konnerth, R. Ritzka, R. Singh and W. Trombik, Munich preprint, to be published;

W. Dünnweber, private communication.

5) M.S. Hussein, B.V. Carlson, O. Civitarese and A. Szanto de Toledo, Phys. Rev. Lett. 54 (1985) 2659;

B.V. Carlson, O. Civitarese, M.S. Hussein and A. Szanto de Toledo, Ann. Phys. in press;

L.F. Canto and M.S. Hussein, to be published;

M.S. Hussein, Proceedings of the International Conference on Reaction Mechanisms, Varenna, Italy. June 1985, to be published.

6) A. De Rossa, G. Inglima, V. Russo and M. Sandoli, Il Nuovo Cimento 58A (1983) 254.

7) W. Norenberg, Phys. Lett. 52B (1974) 289.

8) A.Y. Abul-Magd and M.H. Simbel, Phys. Lett. 83B (1979) 27.

9) K.M. Hartmann, W. Dünnweber and W.E. Frahn, Nucl. Phys. A380 (1982) 170.

10) See, e.g., M. Kawai, A.K. Kerman and K.W. McVoy, Ann. Phys. (NY) 75 (1973) 156.

FIGURE CAPTIONS:

Figure 1: Dinucleus lifetimes as "seen" from different fragment charge channels in the DIC of $^{28}Si + ^{64}Ni$ (Ref. 3). See text for details. The arrow indicates the nuclear passqge time.

Figure 2: The measured charge distributions for $^{28}Si + ^{64}Ni$ (Ref. 3) for several center of mass angles.

Figure 3: The square of the width at half maximum of the charge distributions via the center of mass angle for $^{28}Si + ^{64}Ni$.

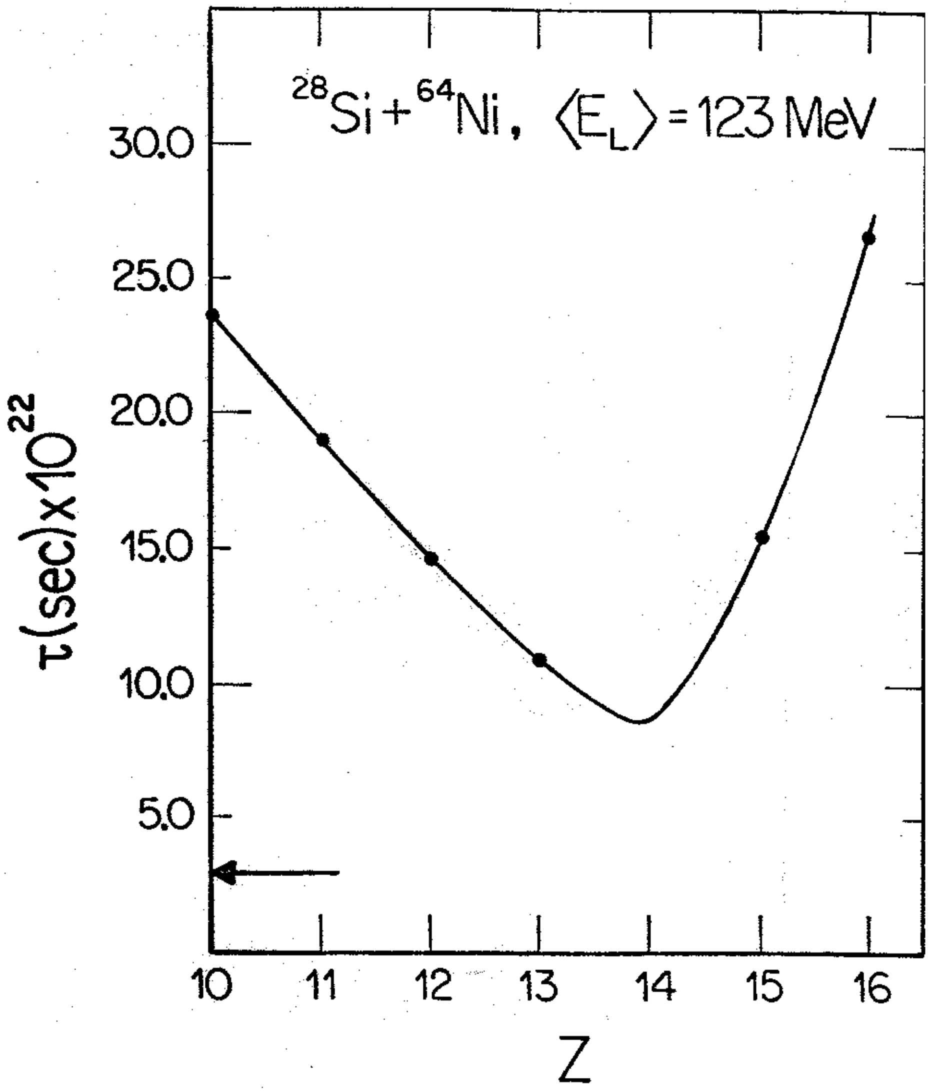

Fig. 1

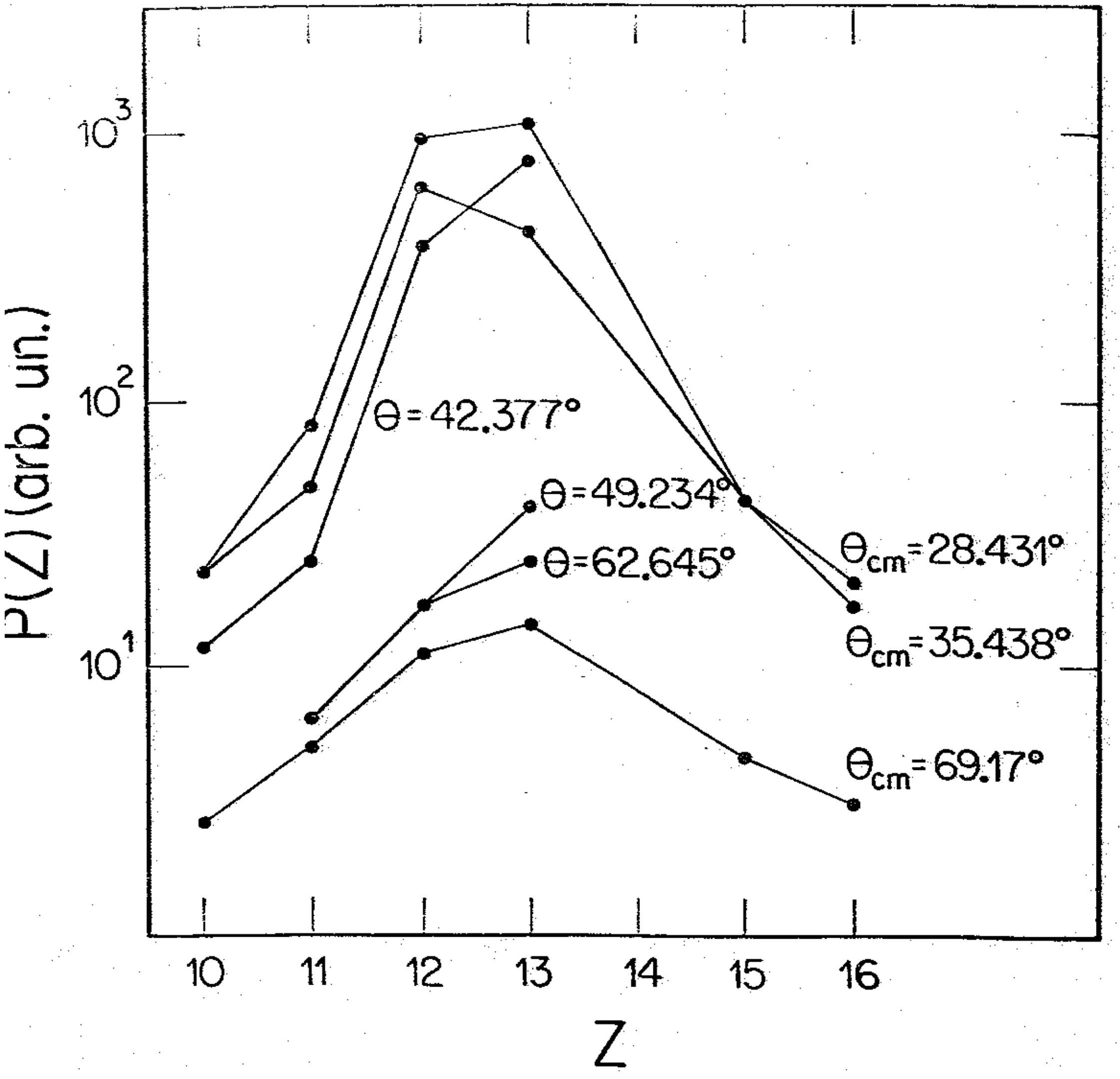
P(Z) (arb. un.)
10^3
10^2
10^1
θ = 42.377°
θ = 49.234°
θ = 62.645°
θcm = 28.431°
θcm = 35.438°
θcm = 69.17°
10
11
12
13
14
15
16
Z

Fig. 2

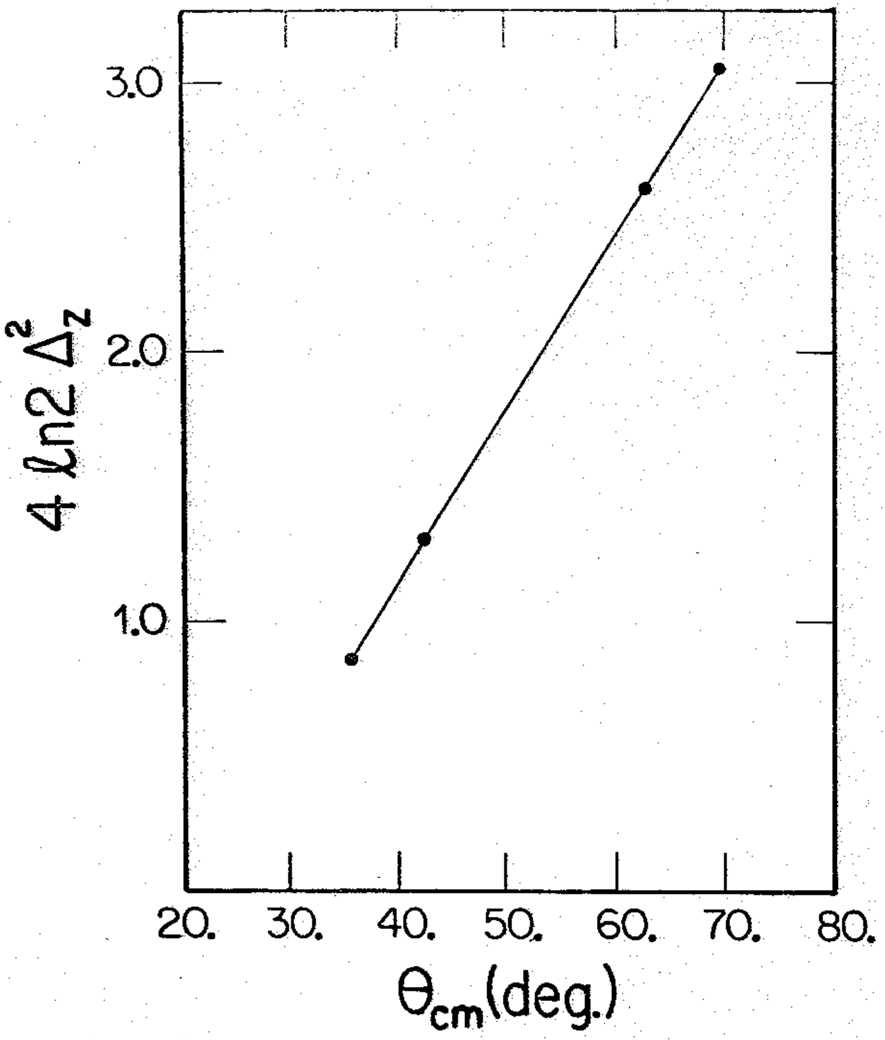
4 ℓn2 Δz²
3.0
2.0
1.0
20.
30.
40.
50.
60.
70.
80.
θcm (deg.)

Fig. 3