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Interaction time evaluation in dissipative heavy ion reactions

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Excitation functions have been measured for different charge products of the $^{28}Si+{}^{48}Ti$ reaction in the laboratory energy range 120–127 MeV in 250-keV steps at $\theta_{lab}=28°$, 32°, and 40°. Coherence energies of dissipative cross sections have been evaluated by statistical fluctuation analysis. The role of the angular dependence of the coherence energy in determining the interaction time is discussed.

I. INTRODUCTION

Very recently increasing interest has been devoted to statistical features of dissipative heavy ion reactions.[1–4] Detailed measurements of excitation functions have evidenced fluctuations in the dissipative cross section, which shows a strong cross correlation between the different fragmentation modes of the decaying intermediate system. The excitation functions have been determined by taking into account only the damped part of the Q-value spectra. Such a procedure does not allow any separation between the individual nuclear states so the statistical analysis was performed on cross sections integrated over a great number of exit channels, all characterized by one value of the fragment atomic number.

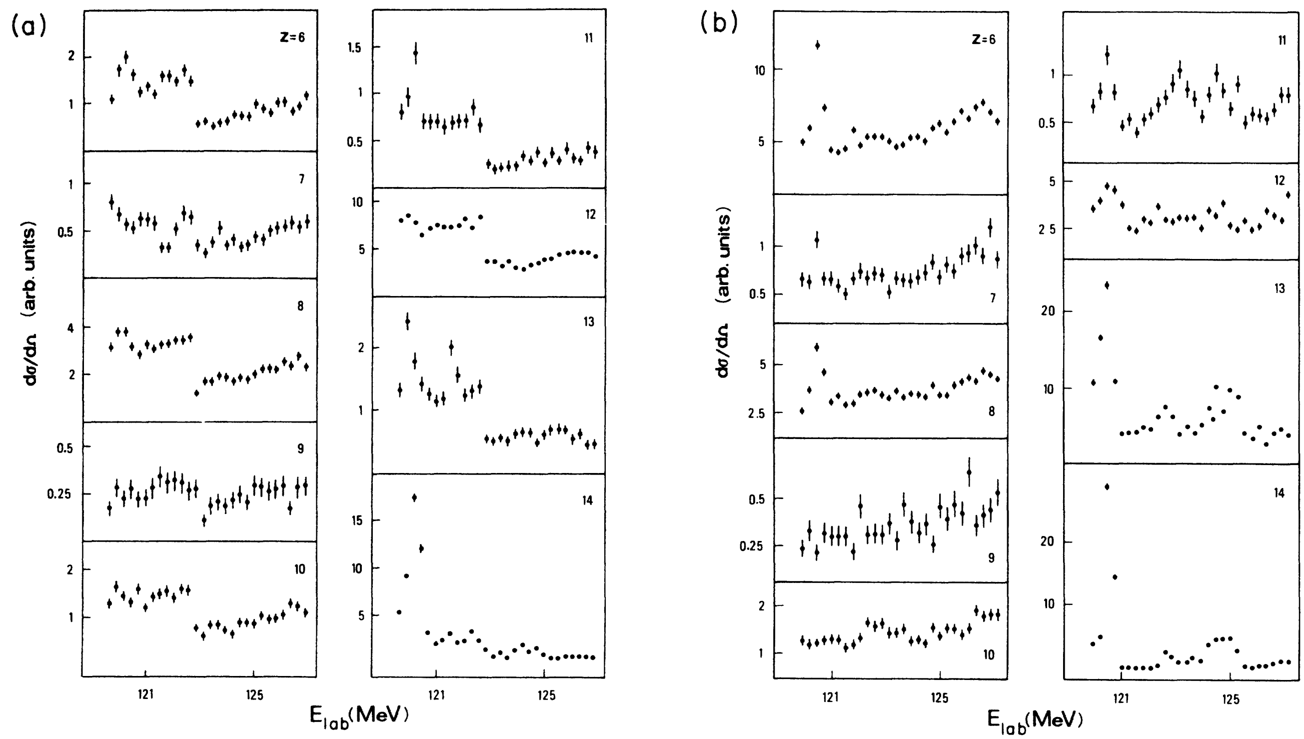
According to Ericson theory these inclusive measurements should wash out all statistical fluctuations since their amplitudes are proportional to the inverse of the number of channels contributing to the measured cross section. On the other hand, the interpretation of the cross section oscillations as resonances similar to those observed in quasimolecular systems[5] does not seem tenable due to the large number of oscillations of comparable magnitude appearing in cross sections. Rather, the observed large cross correlations have been considered as evidence of the formation of a dinucleus in the early stages of the collision. The times extracted from the coherence energies have been related to the mean lifetime of the dinuclear system. In such a way information about the interaction times in dissipative heavy ion reactions could be obtained by the statistical properties of the cross sections.

In previous papers[1] it was shown that the cross section coherence widths decrease as the difference between ejectile and projectile atomic numbers increases. This behavior was observed in proximity of the grazing angle where the contribution of dissipative cross sections is expected to be more significant.[6] As the emission probability depends on the inverse of the mean lifetime, the hypothesis that a larger coherence energy is indicative of a larger emission probability was formulated, according to the appealing picture that final configurations more similar to the entrance channel are more likely produced.

To gain more information on the connection between cross section statistical features and reaction mechanism, we have investigated the angular dependence of the coherence energy in this paper.

II. RESULTS AND ANALYSIS

The excitation function of the $^{28}Si + {}^{48}Ti$ reaction was measured in 158-keV (c.m.) steps at $\theta_{lab}=28°$, 32°, and 40°. The ^{28}Si beam of the XTU Tandem accelerator of Legnaro National Laboratory was used to bombard a self-supporting 40 $\mu g/cm^2$ thick ^{48}Ti target in the energy range $E_{lab}=120-127$ MeV, corresponding to about 1.5 times the Coulomb barrier. The emitted fragments were Z identified by means of three ΔE-E telescopes, two of them employing silicon surface barrier detectors; in the third one the E signal was also delivered by a silicon detector while the ΔE signal came from an ionization chamber. Following the same procedure as described in Ref. 1, only the damped part of each charge identified spectrum was considered in the analysis. In Figs. 1(a), (b), and (c) the corresponding excitation functions, relative to ejectile atomic number $Z=6-14$, are reported for $\theta_{lab}=28°$, 32°, and 40°, respectively. The oscillating behavior is evident while it is difficult to indicate a clear cross correlation between well identified structures appearing in all the excitation functions; such correlations would be expected if a quasimolecular resonant mecha-



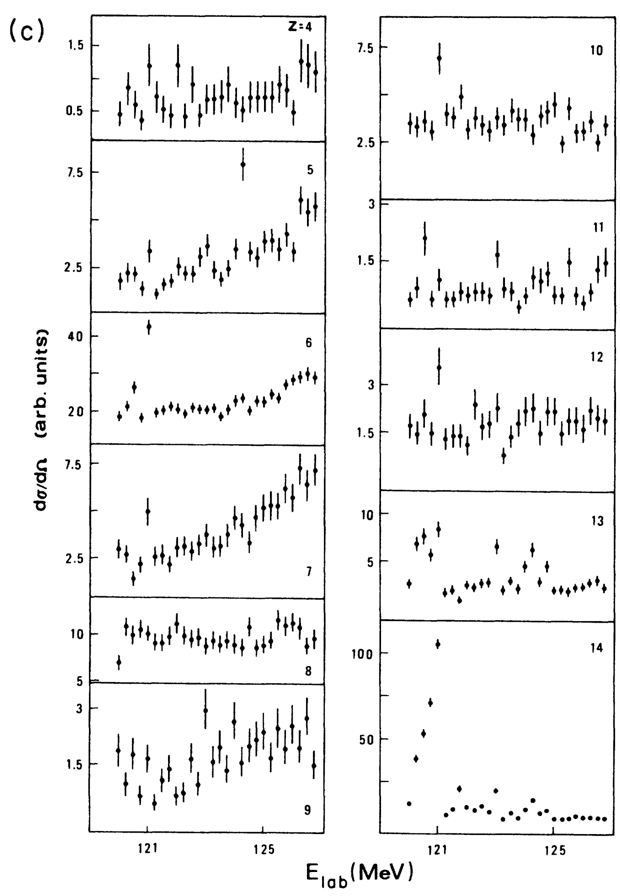


FIG. 1. (a) Excitation functions of the $^{28}Si + {}^{48}Ti$ reaction at $\theta_{lab}=28°$ for different ejectile atomic numbers. (b) Same as (a) for $\theta_{lab}=32°$. (c) Same as (a) for $\theta_{lab}=40°$.

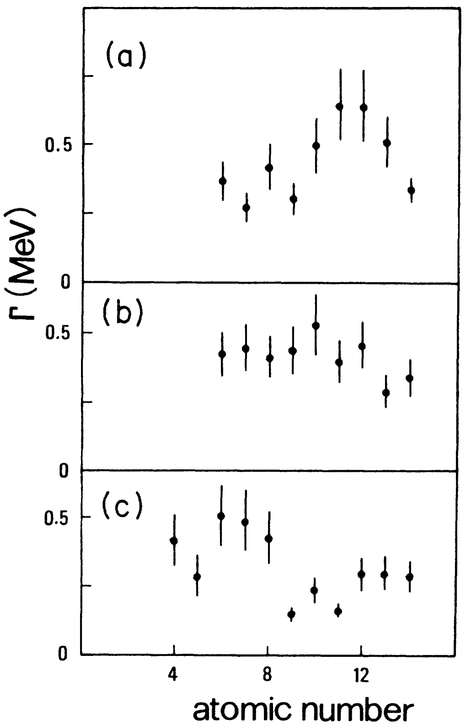


FIG. 2. Coherence energies vs fragment atomic number at $\theta_{lab}=28°$ (a), 32° (b), and 40° (c). The Γ values have been determined by means of the SDM method from the excitation functions of Figs. 1(a), (b), and (c).

nism dominates the entrance channel configuration at a particular excitation energy.

A statistical analysis of the excitation functions was performed by means of the spectral density method (SDM) which has been extensively described elsewhere.[7] In Figs. 2(a), (b), and (c) the extracted coherence energies Γ are reported vs Z, the light fragment atomic number, for the $\theta_{lab}=28°$, 32°, and 40° excitation functions, respectively. In Table I the cross correlation[8,9] coefficients $\rho(Z_1,Z_2)$ are reported for the same excitation functions.

The results of Table I confirm that, as was shown previously[1] for the $^{28}Si + {}^{64}Ni$ system, in the present reaction also there is an average cross correlation of about 60% between the different fragmentation modes. Such a cross correlation is also expected to hold between the unresolved final states characterized by the same atomic number.

According to the conclusions of Ref. 1 this suggests that the fluctuations are due to an entrance channel effect through the excitation of overlapping doorway states in the intermediate dinuclear system. However, comparing the three panels of Fig. 2, one can see that the coherence energy has a clear dependence on the observation angle for $Z=9-12$ while it remains almost constant for the other atomic numbers. It seems difficult to attribute an unambiguous meaning to the times related to each Γ value through the indetermination relation $\tau=\hbar/\Gamma$. In fact by looking at Fig. 2(b) one should conclude that all fragments have almost the same emission probability while from Figs. 2(a) and (c) one could extract the opposite conclusions that the emission of projectile-like fragments is either enhanced or hindered.

In the attempt to clarify these seemingly contradictory results we consider for the moment only the fragments whose excitation functions gave the largest coherence energies reported in Fig. 2(a), namely, $Z=11$ and 12. If a dinuclear configuration for the $^{28}Si + {}^{48}Ti$ system is assumed, it is possible to calculate the orbital moment of inertia[10]

$$\mathcal{J}=\mu(R_1+R_2)^2 \ . \tag{1}$$

A value of $\mathcal{J}=23.03\times10^{-42}$ MeV s^2 is obtained. At the average collision energy here considered the angular velocity

$$\omega=\hbar L/\mathcal{J} \tag{2}$$

has the value $\omega=1.54\times10^{21}$ s^{-1} when for the angular momentum L is assumed the grazing value

$$\hbar L=2\hbar\eta\frac{E_{c.m.}}{V_C}\left[1-\frac{V_C}{E_{c.m.}}\right]^{1/2}, \tag{3}$$

η being the Sommerfeld parameter and V_C the Coulomb barrier. The corresponding rotational period is $T=4.09\times10^{-21}$ s. If the variation of the Γ values versus the emission angle $\Delta\Gamma=\Gamma(\theta_2)-\Gamma(\theta_1)$ is attributed to the time spent by the dinucleus in performing the rotation $\Delta\theta=\theta_2-\theta_1$, one can extract the experimental value of the angular velocity

$$\omega_{exp}=\frac{\theta_2-\theta_1}{\hbar\left[\dfrac{1}{\Gamma(\theta_2)}-\dfrac{1}{\Gamma(\theta_1)}\right]} \ . \tag{4}$$

From Eq. (4) it is possible to determine for each Z value the expected $\Gamma(\theta)$ starting from a reference value $\Gamma(\theta_0)$ in the hypothesis of a constant angular velocity

$$\Gamma(\theta)=\left[\frac{\theta-\theta_0}{\omega\hbar}+\frac{1}{\Gamma(\theta_0)}\right]^{-1} . \tag{5}$$

Some comments on the choice of θ_0 will be given later in this paper. Equations (4) and (5) give a linear relation between the elapsed time and the rotation angle. In Fig. 3 the times corresponding to the coherence energies of Fig. 2 are reported versus the emission angle θ for $Z=11$ (closed circles) and $Z=12$ (closed squares). The linear behavior of both sets of data, lying on two different lines, is evident and gives support to the validity of Eq. (4). However, due to the size of the error bars, we determined an average experimental angular velocity by fitting together all six points of Fig. 3. The extracted angular velocity is $\omega_{exp}=1.5\times10^{20}$ s^{-1}. To further check the validity of Eqs. (4) and (5) we performed the same analysis on the excitation functions of the reaction $^{19}F + {}^{89}Y$ measured at $\theta_{lab}=60°$, 120°, and 160° and reported in Ref. 4. In Fig. 4 the coherence energies determined by means of the SDM method are shown versus the ejectile atomic number. No matter the angle, the coherence energy has its maximum value for projectile-like fragments with $Z=9$. Although a variation of $\Gamma(Z)$ vs θ_{lab} is still present the overall features of the coherence energy are not greatly affected by the emission angle. Moreover if we use Eq. (4) with $\theta_1=120°$ and $\theta_2=160°$ to evaluate the angular velocity of the decaying system, an average value $\omega_{\mathrm{exp}}=3.8\times10^{21}\ \mathrm{s}^{-1}$ is obtained for $Z=8,9,10$ atomic numbers, which compares very well to $\omega=3.09\times10^{21}\ \mathrm{s}^{-1}$, the angular velocity of the $^{19}F+{}^{89}Y$ system at 115.37 MeV collision energy. Calculated from (2) the corresponding rotational period is $T=2.03\times10^{-21}$ s. So, also in the case of the $^{19}F+{}^{89}Y$ reaction, the decrease of the coherence energy versus the emission angle is accounted for by the rotation of the dinuclear system.

Now let us consider Fig. 2 in a comprehensive way to try an explanation of the coherence energy features. Looking at the three panels of the figure we can separate the fragments in two classes according to the behavior of their coherence energy. Class I includes fragments with atomic number close to the projectile and whose coherence energy decreases, when the emission angle increases, until it reaches almost the same value as for the other ejectiles. Class II includes fragments whose coherence energy does not show any significant variation with the emission angle. Inside class I the interaction time is much shorter than the rotational period of the dinucleus. The time we measure through the coherence energy is the time needed for the emission of a fragment at a given angle. Increasing angle brings an increase of the corresponding interaction time by the rotation time. So the coherence energy brings information on both the mean lifetime of the decaying state and on the intermediate system rotation time which is a linear function of the emission angle. This angular dependence of Γ is expected to be introduced by the orbital angular momentum.[3]

To compare the probabilities of the different fragmentation modes it is convenient to determine the minimum time needed by the intermediate system to reach the suitable configuration. For each fragment this occurs at a reference angle θ_0 where the excitation function exhibits the maximum value of the coherence energy, and, hence, the largest emission probability. For atomic

TABLE I. Cross correlation coefficients for the excitation functions of the $^{28}Si+{}^{48}Ti$ reaction measured at $\theta_{\mathrm{lab}}=28°$ (upper), 32° (middle), and 40° (lower). These coefficients are affected by a 20% error due to the finite size of data sample (Ref. 8).

Z	6	7	8	9	10	11	12	13	14
6	1	0.14	0.86	0.73	0.81	0.91	0.70	0.86	0.39
7		1	0.31	0.02	0.28	0.27	0.42	0.07	0.04
8			1	0.70	0.83	0.81	0.79	0.85	0.13
9				1	0.79	0.62	0.69	0.82	0.02
10					1	0.75	0.86	0.82	0.01
11						1	0.55	0.82	0.56
12							1	0.72	0.16
13								1	0.28
14									1

Z	6	7	8	9	10	11	12	13	14
6	1	0.76	0.81	0.01	0.02	0.57	0.74	0.73	0.86
7		1	0.65	0.26	0.16	0.41	0.60	0.60	0.66
8			1	0.15	0.10	0.60	0.80	0.70	0.87
9				1	0.06	0.07	0.10	0.03	0.04
10					1	0.39	0.18	0.03	0.07
11						1	0.72	0.69	0.73
12							1	0.68	0.79
13								1	0.91
14									1

Z	4	5	6	7	8	9	10	11	12	13	14
4	1	0.66	0.41	0.26	0.32	0.06	0.58	0.16	0.49	0.26	0.11
5		1	0.39	0.48	0.08	0.16	0.41	0.11	0.37	0.46	0.10
6			1	0.01	0.31	0.04	0.60	0.55	0.48	0.48	0.17
7				1	0.12	0.31	0.13	0.16	0.16	0.45	0.01
8					1	0.11	0.66	0.51	0.56	0.07	0.20
9						1	0.25	0.12	0.11	0.36	0.29
10							1	0.38	0.50	0.22	0.30
11								1	0.38	0.40	0.21
12									1	0.32	0.30
13										1	0.09
14											1

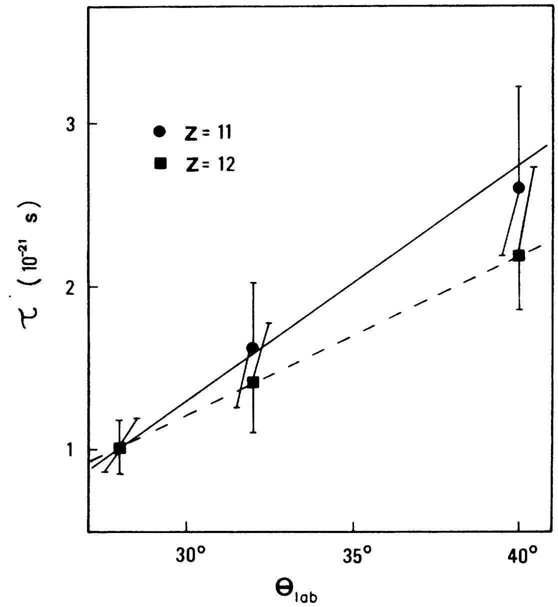


FIG. 3. Times corresponding to the coherence energies of Fig. 2 vs emission angle for atomic numbers $Z=11$ (closed circles) and $Z=12$ (closed squares). The corresponding straight lines obtained by means of a least squares fit are also shown.

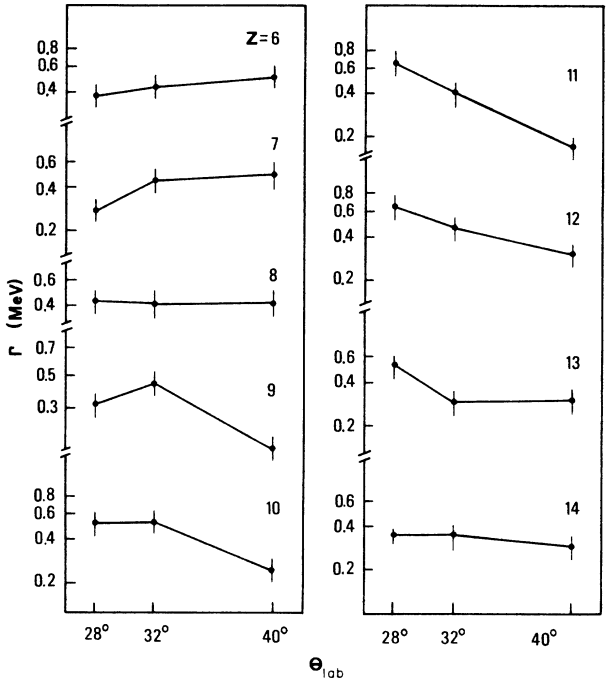


FIG. 5. Coherence energies vs emission angles for the $^{28}Si + ^{48}Ti$ reaction.

numbers close to the projectile, θ_0 is expected to be smaller than the grazing angle θ_G as dissipative reactions are characterized by impact parameters smaller than the grazing one.

In Fig. 5 the coherence energy is reported versus the three values of $\theta_{lab}=28°$, 32°, and 40° here considered for the $^{28}Si + ^{48}Ti$ reaction. It is evident that none of the curves relative to atomic numbers very close to the projectile shows a maximum. This behavior can be justified by observing that, as $\theta_G \approx 30°$, the maximum is expected at an angle θ_0 more forward than those here considered.

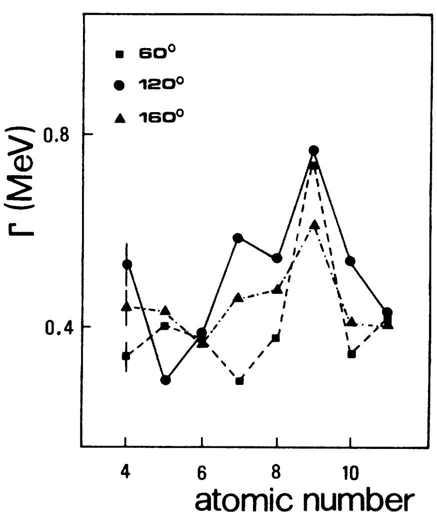


FIG. 4. Coherence energies vs fragment atomic number for the $^{19}F + ^{89}Y$ reaction at $\theta_{lab}=60$, 120, and 160° (Ref. 4). The Γ values have been determined by means of the SDM method.

Fragments with atomic number belonging to class II are characterized by angle independent reaction times. This indicates that in the angular range here explored these fragments have almost constant emission probability and the production of the proper intermediate system configuration requires at least an interaction time $\Delta t \simeq 1.5 \times 10^{-21}$ s. This time corresponds to a coherence energy $\Gamma \approx 500$ keV. In this case the emission resembles more the decay of a compound nucleus than a deep inelastic collision. Should this latter mechanism also be effective, the process would be characterized by a reference angle θ_0 such that the variation of the coherence energy $\Gamma(\theta)$ with respect to the angles considered here is out of the sensitivity of our analysis.

It is to be noted that the experimental angular velocity is 1 order of magnitude smaller than the "theoretical" one [Eq. (2)] in the system $^{28}Si + ^{48}Ti$. This accounts for the strong dependence of Γ on the emission angle and points out the dissipative character of this reaction. The same arguments indicate a less dissipative nature of the $^{19}F + ^{89}Y$ reaction whose experimental and grazing angular velocities compare fairly well, in agreement to the weak angular dependence of Γ.

III. CONCLUSIONS

In this paper it has been shown that statistical properties of the cross sections can provide accurate information on the interaction times in dissipative heavy ion reactions. The approach is similar to that of Nörenberg[11] who related the absolute interaction time τ to the deflection angle

$$\tau(\theta)=\frac{\theta'_G-\theta}{\bar{\omega}}=\frac{\mathcal{J}(\theta'_G-\theta)}{\hbar L_G} . \tag{6}$$

However, in Eq. (6) θ'_G is a free parameter playing the role of an appropriate grazing reference angle and the angular velocity is generally assumed to have the dinucleus grazing value. In the present analysis the angular variation of the coherence energy allows a parameter free determination of the rotation time

$$\Delta\tau=\frac{\hbar}{\Gamma(\theta)}-\frac{\hbar}{\Gamma(\theta_0)}$$

and, hence, of the experimental angular velocity of the decaying dinuclear system. Moreover one can achieve a better understanding of the reaction mechanism than is possible on the basis of angular distribution consideration only. In fact the statistical features of the cross section give a direct evaluation of the time scale of fragment emission. The absolute measurement of the interaction times requires the knowledge of the reference emission angle θ_0 which has to be determined by accurate measurements of coherence energy angular dependence. This would allow a direct comparison of the realization probability among the different fragmentation modes. Experimental work aiming at this is in progress.

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[1]A. De Rosa *et al.*, Phys. Lett. **160B**, 239 (1985).

[2]A. Glaesner *et al.*, Phys. Lett. **169B**, 153 (1986); R. Lucas *et al.*, Proceedings of International Nuclear Physics Conference, Harrogate, United Kingdom, 1986, Vol. 1, p. 287; R. Bonetti and M. S. Hussein, Phys. Rev. Lett. **57**, 194 (1986).

[3]D. M. Brink and K. Dietrich, Z. Phys. A **326**, 7 (1987).

[4]T. Suomijärvi *et al.*, Phys. Rev. C **36**, 181 (1987).

[5]*Nuclear Molecular Phenomena,* edited by N. Cindro (North-Holland, Amsterdam, 1978); *Resonant Behavior of Heavy Ion Systems,* edited by G. Vourvopoulos (National Printing Office, Athens, 1981).

[6]W. V. Schroeder and J. R. Huizenga, Annu. Rev. Nucl. Sci. **27**, 465 (1977).

[7]A. De Rosa, G. Inglima, V. Russo, and M. Sandoli, Phys. Rev. C **27**, 2688 (1983); Nuovo Cimento A **58**, 254 (1980); Istituto Nazionale di Fisica Nucleare Report BE-80/8, 1980, and references therein.

[8]W. Von Witsch, P. Von Brentano, T. Mayer Kuckuk, and A. Richter, Nucl. Phys. **80**, 394 (1966).

[9]I. Hall, Phys. Lett. **10**, 199 (1964).

[10]M. Le Fort and C. Ngo, Riv. Nuovo Cimento **12**, 1 (1979).

[11]W. Nörenberg, Phys. Lett. **52B**, 289 (1974).