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Level density of hot nuclei with $A \leq 40$

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The light charged particles emitted from hot ^{40}Ca compound nuclei, populated at excitation energy $E_x = 94$ MeV and $\langle J \rangle = 20.5\hbar$ by the reaction 130 MeV ^{16}O on ^{24}Mg, have been studied. Energy spectra of protons and alpha particles, measured in coincidence with evaporation residues and with a selection of multiple-alpha chains, have been compared with the predictions of Monte Carlo statistical model calculations. The comparison shows that the level density of hot nuclei with $A \leq 40$, needed to account for the measured quantities, is well predicted by the Fermi-gas model using a level-density parameter $a_{\text{eff}} = A/8$ MeV^{-1} up to excitation energy $\langle E_{\text{th}}/A \rangle \sim 1.7$ MeV. In agreement with theory, light hot nuclei do not show the transition from $a_{\text{eff}} = A/8$ MeV^{-1} to $a_{\text{eff}} \sim A/13$ MeV^{-1} evidenced in the $A \sim 160$ mass region for the same range of excitation energies E_{th}/A. The analysis of the alpha-particle spectra shows that the effects associated with the angular-momentum-induced deformations depend on the entrance channel characteristics and, in this case, are very small compared with those evidenced in the past for compound nuclei in the region $A = 50-70$.

I. INTRODUCTION

The studies of nuclear matter at high excitation energies, the so-called "hot nuclei," identify today an important field of investigation in nuclear physics [1,2]. These studies have generally benefitted from the availability of heavy-ion beams, which allow the production of compound systems at different excitation energies and angular momenta, so that the effects related to both parameters can be discriminated and studied.

So far, a large experimental effort has been devoted to studies of hot nuclei with mass $A \geq 100$ [3] where the spin-related phenomena are small compared to temperature effects and the range of excitation energies already investigated is wide. By triggering on evaporation residues and/or fission fragments, statistical and dynamical phenomena have been isolated in the decay of the hot nucleus.

In particular, the temperature dependence of the nuclear level-density parameter $a_{\text{eff}} = A/K$ MeV^{-1} (i.e., the change of K from the low-temperature value $K = 8$ to $K \sim 13$ at temperature $T \sim 4-5$ MeV) has been experimentally determined in $A \sim 160$ nuclei [4–6]. Theoretically this has been connected with the temperature dependence of the nucleon effective mass [7]. Further knowledge of the level density in other mass regions is not only interesting in itself, but also of crucial importance in the study of the limits of nuclear collectivity pursued by measuring the giant dipole resonance (GDR) strength function in hot nuclei [8] and in nuclear astrophysics [9].

Moreover, a number of studies have been dedicated to the decay of light-mass ($A \leq 100$) compound nuclei formed in heavy-ion-induced fusion reactions at excitation energies around 100 MeV [10,11]. Energy spectra of the emitted charged particles have been compared with statistical model calculations to determine the shape and structure of the excited nucleus at high spin. It was found in several cases that, for spin regions where the rotating liquid-drop model (RLDM [12]) predicts nearly spherical shapes, experimental data are very well described by standard statistical model calculations [13]. When the angular momentum is increased to values for which the RLDM predicts significant deformations, the calculations employing RLDM yrast lines with standard level-density formulations and transmission coefficients lead to more high-energy and fewer low-energy (near barrier) α particles than experimentally observed. This spin effect is relatively large around mass $A \sim 60$ and has been interpreted as due to the relaxation of the shape degree of freedom during the particle emission [14] or, alternatively, to a dependence of the nuclear level density of the deformation [10,15] much larger than the one predicted by theory [16].

We present here a complete study of the decay of a highly excited ($T \sim 3.7$ MeV) light compound nucleus, ^{40}Ca, formed in the fusion of 130 MeV ^{16}O with ^{24}Mg.

This work was motivated by the goal of studying the level-density parameter $a_{\text{eff}} = A/K$ MeV^{-1} dependence on the nuclear temperature in light systems and investigating the spin effects persistence in a hot compound nucleus.

II. EXPERIMENTAL DETAILS

The experiment was performed at the XTU Tandem Accelerator of the Laboratori Nazionali di Legnaro, Italy. The 130-MeV ^{16}O beam was focused onto a 290-μg/cm^2 ^{24}Mg target. A linear momentum transfer close to 100% is expected for this reaction [17]. The resulting ^{40}Ca compound nucleus is formed at excitation energy $E_x = 94$ MeV and with a spin distribution which extends up to the critical angular momentum for vanishing fission barrier, $J_{Bf=0} = 31.5\hbar$, as shown in Fig. 1. The thermal excitation energy per nucleon is $E_{\text{th}}/A = 1.7$ MeV, after correction for the average rotational energy. The corresponding nuclear temperature T is $T = 3.7$ MeV (using the level-density parameter $a_{\text{eff}} = A/8$ MeV^{-1}).

A second short run was performed at a lower bombarding energy $E_{\text{beam}} = 60$ MeV, corresponding to $E_x = 52$ MeV and maximum angular momentum $J_{\max} = 22.5\hbar$. This ancillary measurement was made to provide a suitable check for statistical model calculations in more standard conditions (see Ref. [13]).

Evaporation residues were detected by a large solid angle telescope (ERT) using an ionization chamber as ΔE and a silicon strip detector (7 strips, 6×4 cm^2, 400 μm thick) to measure the residual energy. This telescope was placed at $\theta_{\text{lab}} = +13°$ covering $\Delta\theta_{\text{lab}} = 7°$.

Light particles were detected with four telescopes (LPT) placed at $\theta_{\text{lab}} = -15°$, $-30°$, $-60°$, and $-150°$. The $\theta_{\text{lab}} = -150°$ telescope was made with three silicon detectors (thickness 15, 200, and 1000 μm), whereas the others consisted of three silicon detectors (thickness 20–50, 150–200, and 1000 μm) backed by a 1-cm-thick CsI(Tl) scintillator with photodiode read-out.

A light charged-particle hodoscope (LPH) made of eight ΔE-E telescopes each having a 3×4-cm^2 active area was placed in the plane perpendicular to the beam at 6 cm from the target in the forward hemisphere.

Energetic γ rays were detected at $\theta_{\text{lab}} = 90°$ by a 10.2 cm $\times$ 10.2 cm BGO counter [18], surrounded by a plastic scintillator anticoincidence detector and by a 10-cm-thick lead shield. Time of flight over a 100-cm path was used to separate γ rays from neutrons, using the start signal from the charged-particle hodoscope.

During the main data-taking at $E_{\text{beam}} = 130$ MeV we have collected coincidences between evaporation residues and light particles in LPT, coincidences between light charged particles in the hodoscope (LPH), and evaporation residues (ERT) or light particles in the telescopes (LPT) or γ rays. At $E_{\text{beam}} = 60$ MeV light particle singles in LPT and some coincidences LPT-ERT were obtained.

III. EXPERIMENTAL RESULTS

Figure 2 shows a sample of ΔE-E_{res} scatter plot for heavy fragments detected in the ERT for the strip at $\theta_{\text{lab}} = 10°$. An inspection of the energy spectra (not reported) reveals that fragments with $Z \geq 12$ originate from fusion-evaporation reactions, as suggested also by previous experimental works on systems in this mass region [19] and by evaporation calculation predictions [13]. Two conditions were imposed on the ERT data to separate evaporation residue (ER) ($Z \geq 12$) and projectilelike fragments (PLE) ($6 \leq Z \leq 11$).

We show in Fig. 3 the angular distributions and the alpha/proton ratios of particles detected in LPT for the two gates on ERT. We note that the yields of light

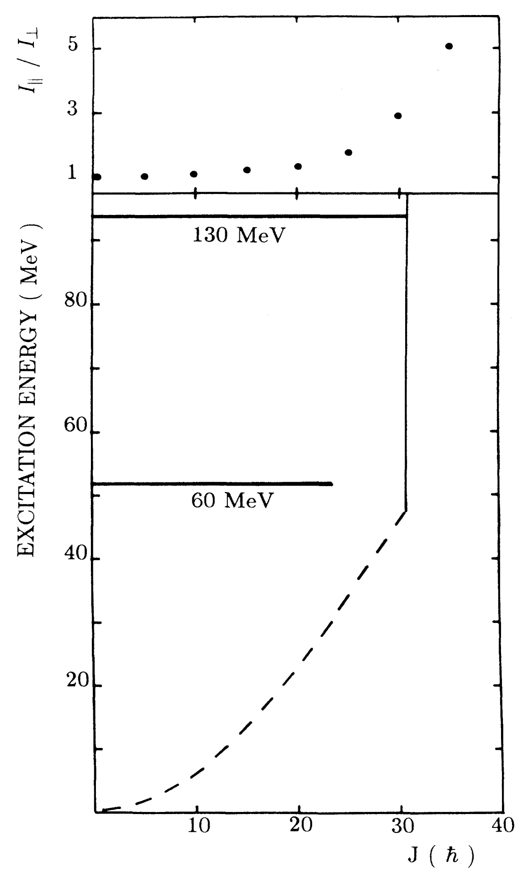

FIG. 1. Yrast plot for ^{40}Ca. Yrast line is from Ref. [30]. The heavy horizontal lines indicate the angular momentum regions and excitation energies associated with the fusion reactions studied. The vertical line marks the angular momentum for vanishing fission barrier. In the upper part are shown predictions from RLDM [12] for the ratio of the moments of inertia indicating the onset of deformation with increasing angular momentum.

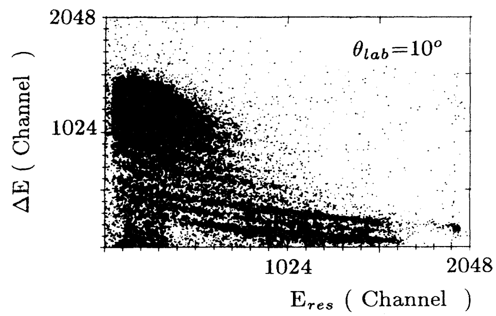

FIG. 2. ΔE-$E_{\rm res}$ plot for heavy fragments detected in the ERT.

charged particles at forward angles are comparable for PLF and ER events. The alpha/proton ratio is very large at forward angles for PLF, due to the favored population of even-Z projectilelike fragments, as can be seen directly from the scatter plot in Fig. 2. To investigate further the characteristics of the alpha-particle emission we have studied the multiplicity and the spatial distributions of the events in the hodoscope LPH. In Fig. 4 the measured multiplicity distributions of alpha particles in the LPH for the two gates on ERT is shown. Surprisingly the measured distributions are very similar. The count ratio of the left half to the right half of the hodoscope, as a function of the alpha multiplicity, is reported in Fig. 5. As the heavy fragments were detected in ERT at right angles, linear momentum conservation makes the left part favored for the alpha-particle detection. This kinematical focusing is larger for events with higher alpha multiplicity. The effect is destroyed gating on the PLF, because of the two-body nature of these events.

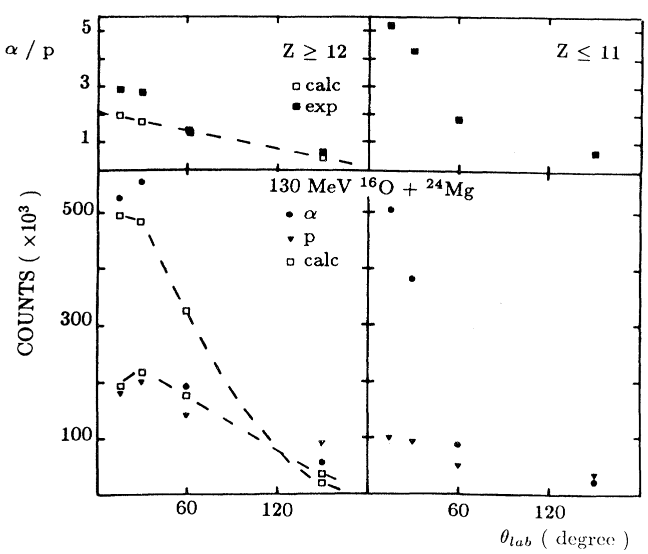

FIG. 3. Angular distribution and alpha/proton ratio for the light particles emitted in the reaction 130 MeV ^{16}O+ ^{24}Mg. Results from CACARIZO calculation are also reported. The predicted angular distributions are normalized to the experimental points separately for alpha particles and protons.

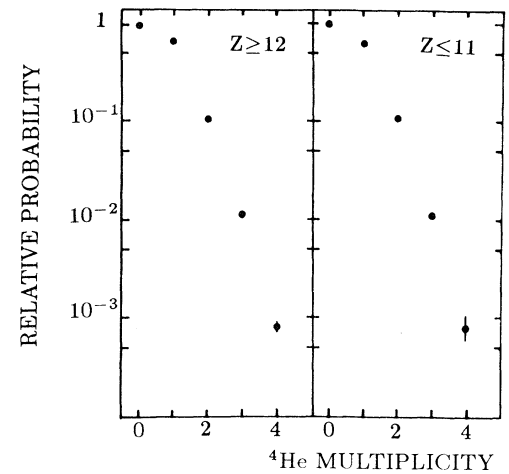

FIG. 4. Relative probability distributions for alpha-particle multiplicity as measured in the LPH in coincidence with fragments with $Z \geq 12$ and $Z \leq 11$ in ERT (130 MeV ^{16}O on ^{24}Mg).

As a first result, a large yield of charged particles originating from two-body events has been evidenced. The multiplicity distribution of those alpha particle is comparable to that associated with ER. This fact implies that neither charged-particles singles nor the selection of the higher charged particle multiplicity, as it was done in the past for other systems [14], can be used in the present case to study the hot compound nucleus. Therefore the LPT spectra at 130 MeV bombarding energy analyzed in the following to study temperature and spin effects are only those taken in coincidence with the detected ER (fragment with $Z \geq 12$). The energy spectra of protons and alpha particles detected in coincidence with ER are shown in Figs. 6 and 7, respectively. In Fig. 8 we present the energy spectra of alpha particles detected in the LPT at $\theta_{\rm lab}$ = 15°, 30°, and 60° in coincidence with the evaporation residue in the ERT and with the condition of having

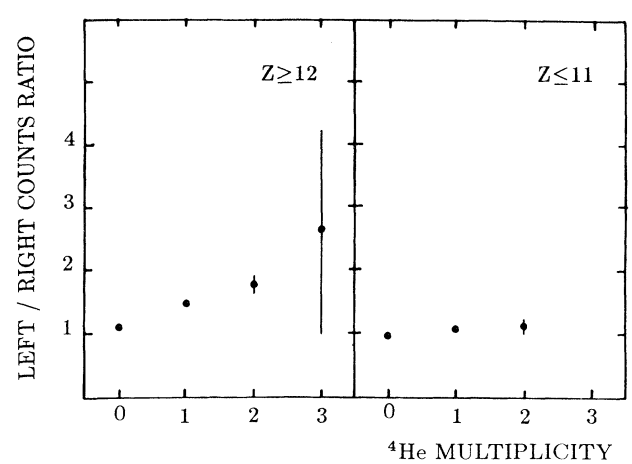

FIG. 5. Left-to-right event ratio in LPH as a function of the alpha-particle multiplicity in coincidence with fragments with $Z \geq 12$ and $Z \leq 11$ in ERT placed at right angles (130 MeV ^{16}O on ^{24}Mg).

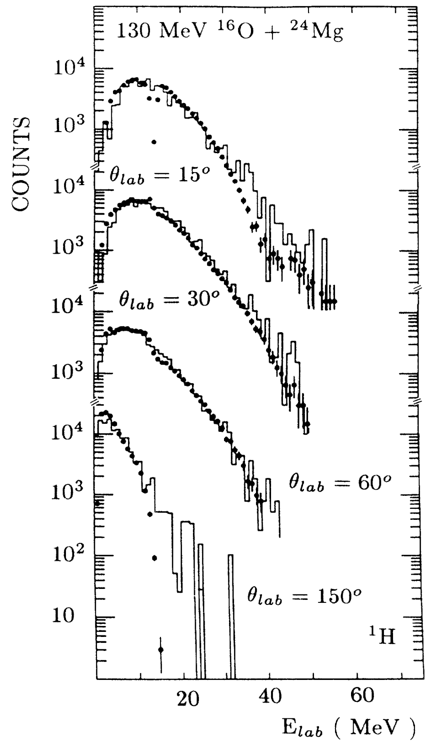

FIG. 6. Proton spectra in coincidence with ER ($Z \geq 12$) for the reaction 130 MeV ^{16}O on ^{24}Mg. Histograms are results from standard statistical model calculations.

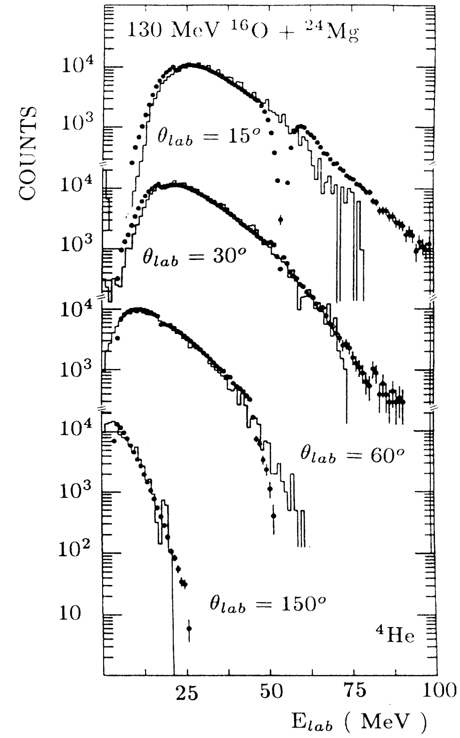

FIG. 7. As in Fig. 6 but for alpha particles.

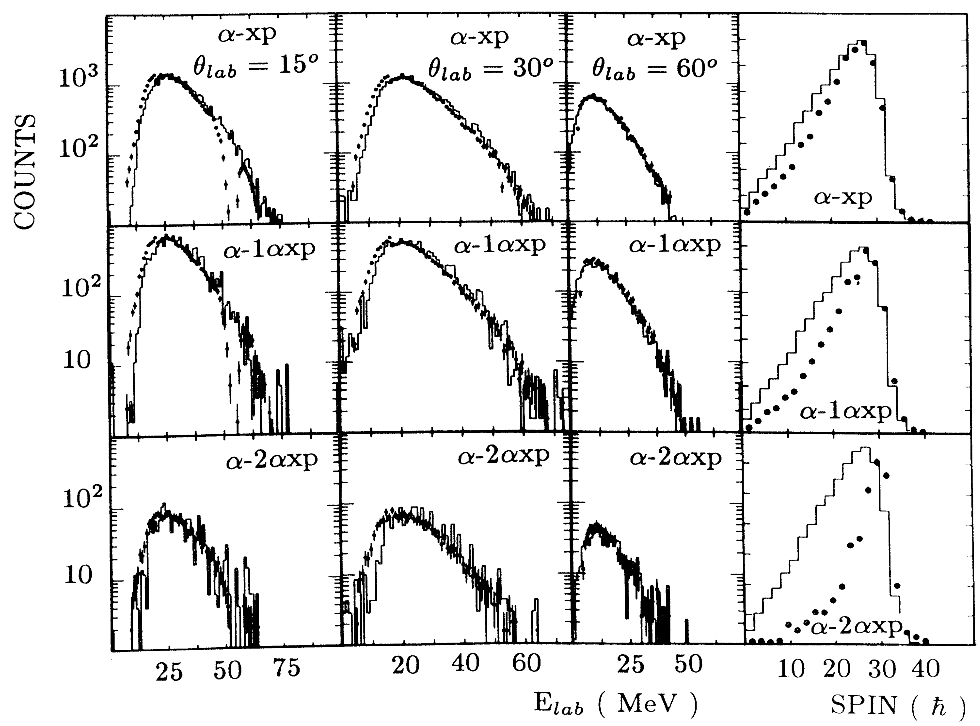

FIG. 8. Comparison between experimental and simulated alpha-particle spectra detected in LPT at θ_{lab} = 15°, 30°, and 45° in coincidence with ER in the ERT and with x protons, one α and x protons, and two α's and x protons in LPH. The predicted spin distribution for the different threefold coincidences are compared with the spin distribution of the hot emitter ^{40}Ca to show the spin selectivity obtained by selecting multiple-alpha chains in the decay of the compound nucleus.

(a) x protons, (b) x protons and one α, and (c) x protons and two α's detected in the LPH. Because of the large amount of angular momentum carried away by the α particles, the selection of deexcitation chains with an increasing number of emitted alpha particles depletes automatically the lower part of the spin distribution of the compound nucleus, isolating the decay from more deformed states.

At the lower bombarding energy ($E_{\rm beam}=60$ MeV) the yield of charged particles from reactions different from the fusion evaporation is expected to be much lower. Single charged-particle spectra at bombarding energy of 60 MeV are reported in Figs. 9 and 10. The corresponding angular distributions are in Fig. 11. Model calculations account well for the angular distribution of alpha particles but not of protons. This has been discussed in a previous paper [10].

In the present experiment γ rays were detected in coincidences with charged particles in the LPH, following the recent measurement of the ^{32}S$+^{27}$Al reaction at 190 MeV [20]. In the latter case the LPH trigger provided a valid tagging of the compound nucleus decay due to the low yield of alpha particles after two-body reactions. As discussed above, this condition is not fulfilled for the ^{16}O$+^{24}$Mg reaction at 130 MeV, causing the possible contamination of the γ-ray LPH coincidences by reaction events different from compound nucleus decay. Also in the γ-ray case, a selective trigger on ER is needed to isolate signals from the decay of the hot nucleus.

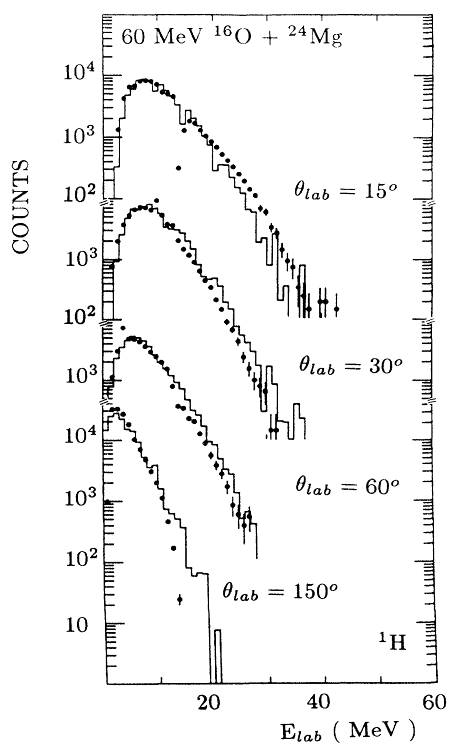

FIG. 9. Proton spectra (singles) for the reaction 60 MeV ^{16}O on ^{24}Mg. Histograms are results from standard statistical model calculations.

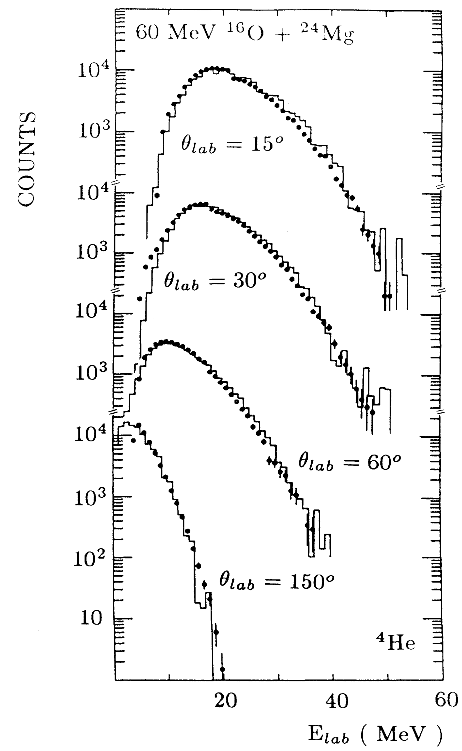

FIG. 10. As in Fig. 9 but for alpha particles.

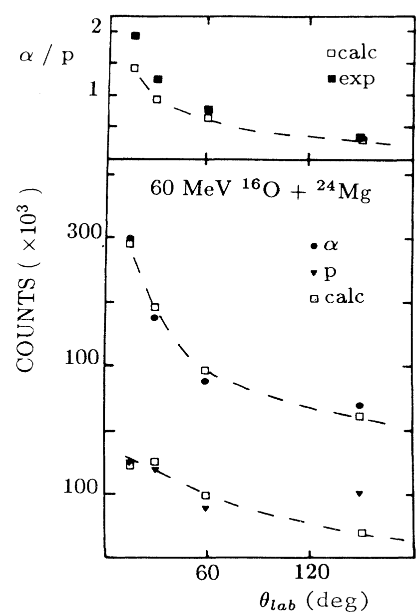

FIG. 11. Angular distribution and alpha/proton ratio for the light particles (singles) emitted in the reaction 60 MeV ^{16}O$+^{24}$Mg. The lines indicate results from CACARIZO calculation. The predicted angular distributions are normalized to the experimental points separately for alpha particles and protons.

IV. COMPARISON WITH STATISTICAL MODEL PREDICTIONS

In recent years, a large number of experimental data from fusion-evaporation reactions have been compared with results from statistical model calculations [21].

The comparison between the energy spectra of the emitted particles and those predicted by model calculations offers information on the evaporation process often washed out in the averaging which produces the mass (or charge) distribution of the final evaporation residue. The high-energy slope of particle spectra is a sensitive probe of the energy dependence of the level density for those reaction products which carry a negligible amount of angular momenta and are therefore insensitive to the possible spin dependence of the phase space accessible to the decay. This is well known in the case of energetic γ rays emitted in the decay of the GDR built on excited states and of nucleon evaporation. On the other hand, alpha particles (or generally complex clusters) carry sizable amounts of angular momentum, being therefore an excellent probe of both excitation energy and spin dependence of the accessible phase space.

The availability in the present case of protons as well as alpha-particle spectra is the basic condition to distinguish between possible spin- and temperature-induced effects.

CASCADE standard statistical model calculations in the mass range of interest for this work and excitation energies up to $E_x \sim 80$ MeV are discussed and compared with experimental evaporation residue distributions in Ref. [13]. In the present work we have used CACARIZO, the Monte Carlo version of the CASCADE code [22]. The use of a Monte Carlo simulation offers the opportunity of comparing spectra in the laboratory frame, with a detailed account being taken of experimental geometry and detector thresholds. The comparison between experimental distributions and the CACARIZO simulations is free from a possible bias originating in the conversion of particle spectra from the laboratory to center-of-mass frame using average source velocity and emission angles, which can be quite severe for light compound nuclei.

For the calculations presented in the following we have used the standard input set reported in Table I with input values mainly taken from Ref. [13].

For sake of a general test of the model, the results of CACARIZO calculations are compared with proton and alpha-particle spectra taken at 60 MeV bombarding energy in Figs. 9 and 10, respectively. In Fig. 11 calculations are compared with angular distribution data and the alpha/proton ratio. It turns out that the bulk of the data is correctly described by the calculations although some deviations are evident. In particular, the high-energy tail of the proton spectrum indicates that calculations might be improved by using a slightly different energy parametrization of level density [31]. Since the experimental data result from singles measurements, we avoid further speculations or comparison with more refined model calculations.

In Figs. 3, 6, and 7 we present the comparison of the statistical model prediction with the experimental data taken at 130 MeV bombarding energy. Model calculations with standard parameters give an account as good as that for the lower bombarding energy of the shapes of the particle spectra, as well as of the angular distributions and alpha/proton ratio. The two major features which arise from this comparison are (1) the level-density parameter $a_{\rm eff} = A/8$ MeV^{-1} also describes well the slope of the proton spectra for the range of temperature involved in the 130-MeV irradiation; and (2) when the spin of the emitter is increased, the alpha-particle spectra do

TABLE I. Evaporation calculations using CASCADE.

Angular momentum distribution in the compound nucleus
(A) 60 MeV ^{16}O+^{24}Mg: $J_{\rm max}=22.5\hbar$, diffuseness $\Delta=1.3\hbar$
(B) 130 MeV ^{16}O+^{24}Mg: $J_{\rm max}=31.5\hbar$, diffuseness $\Delta=1.3\hbar$
Myers droplet model with Wigner term mass formula [23]
Optical potential for emitted particles
(1) neutrons, Wilmore and Hodgson [24]
(2) protons, Perey [25]
(3) α particles, Huizenga and Igo [26]
Level-density parameters at low excitation ($E^* \leq 10$ MeV)
(1) Fermi-gas level-density formula [27] with empirical parameters from Dilg [28]
(2) effective moment of inertia $\mathcal{J}=0.85\mathcal{J}_{\rm rigid}$
Level-density parameters at high excitation ($E^* \geq 15$ MeV)
(1) Fermi-gas level-density formula [27] with parameters from liquid-drop model [29]
(2) Level density parameter $a_{\rm eff}=A/$DALDM MeV^{-1}, DALDM$=8$
Yrast line
subroutine BARFIT, Sierk, LANL, Group T9 [30]
γ-decay width (Weisskopf units)
(1) $E1$ decay: $B(E1)=10^{-3}$
(2) $M1$ decay: $B(M1)=5\times10^{-2}$
(3) $E2$ decay: $B(E2)=5$

not show the dramatic deviation between calculation and experimental data already evidenced in the mass $A \sim 60$ region. We note also that the yield of low-energy particles is underestimated in the calculations for protons as well as for alpha particles.

To obtain a more selective test of the model, we present in Fig. 8 the comparison between triple-coincidence spectra (LPT-ERT-LPH) with the corresponding Monte Carlo statistical model calculation. In Fig. 8 are also reported the calculated spin distributions of events populating the different spectra showing the selection operated by increasing the number of detected alpha particles. The same picture reported above for LPT-ERT coincidences is obtained from Fig. 8: the high-energy tail of the spectra is very well described by calculations using a standard phase space (i.e., energy and spin dependence of level density as given by the parameter $a_{\rm eff} = A/8$ MeV^{-1} and the Sierk yrast line) also for the decay from high spin states, whereas the low-energy part of the spectra are severely underestimated by model calculations.

V. DISCUSSION

A. The level density of hot nuclei with $A \leq 40$

In the Fermi gas (FG) approach to the nuclear level density, a key quantity is the level-density parameter a, which is simply related to the density of single-particle levels $g(\epsilon_F)$ at the Fermi energy ϵ_F

$$a = \frac{\pi^2}{6} g(\epsilon_F) ,$$

and reflects the properties of the single-particle potential.

In the same conditions, the excitation energy E_x is related to the nuclear temperature T by

$$E_x = aT^2 .$$

According to this relation, the experimental knowledge of E_x and T allows the definition of an effective level-density parameter $a_{\rm eff}$.

For excitation energies of the order of the neutron separation energy, $E_x \sim 8$ MeV, the empirical value of $a_{\rm eff}$ is $a_{\rm eff} \approx A/8$ MeV^{-1}, where A is the mass number, to be compared with the FG value $a \approx A/15$ MeV^{-1}.

The disagreement between the FG value and the one at low excitation energy is understood in terms of the finite size of the nuclei and of the increase of the nucleon effective mass at the Fermi energy produced by the coupling of the single-particle motion to other degrees of freedom. This last correlation is predicted [7,32] to disappear for a temperature larger than the one of typical low-lying excited states, in agreement with the experimental findings for $A \simeq 160$. Therefore, the transition temperature is expected to scale roughly with $A^{-1/3}$, at least for double magic nuclei. Very recent calculations seem to support this picture. Using the results of Ref. [7] for ^{208}Pb, the excitation energy per nucleon needed in the $A \simeq 40$ region for the transition to FG values should be of the order of 3 MeV [33]. Microscopic calculations of the level density in ^{40}Ca show a rather steep fall of the parameter $a_{\rm eff}$ for temperatures between $T = 3$ and 5 MeV [34]. The temperature dependence of $a_{\rm eff}$ predicted by the two models, although with some differences, is qualitatively similar. The fact that light nuclei involved in the decay of the hot ^{40}Ca retain the $a_{\rm eff} = A/8$ value up to the largest excitation energies reached in this work, can be taken as a qualitative support for the theoretical predictions. Exact determination of the transition energy in different mass ranges should directly reveal the role of the relevant degree of freedom, providing a more quantitative test of the current theories.

B. Alpha emission from the hot ^{40}Ca

The influence of angular momentum induced deformations on the shape of the evaporated particle spectra has been studied so far in a variety of medium-light compound nuclei [10,11], whereas it becomes negligible for mass larger than $A \sim 100$ because the high angular momentum states are progressively depleted by the opening of the fission channel. It was shown that its major signature is the overproduction of the energetic alpha particles in model calculations. The statistical model predicts that the high spin states should decay essentially by emitting alpha particles in the first step of the deexcitation chain, as already expected from semiclassical considerations. These alpha particles are particularly energetic because they are sampling the part of the phase space close to the yrast line where the spin dependence of the level density is very strong. As a matter of fact, the high-energy tail of the total computed spectrum is essentially determined by these first-step alpha particles emitted from high spin states.

Whichever the underlying physics is, the fit of the experimental spectrum is obtained by a spin-dependent change of the phase-space available for the decay which results in an increase of proton emission from the high spin states at the expense of the alpha-particle yield.

Two hypotheses have been formulated in the past. First it was suggested [10] that the spin dependence of level density for deformed nuclear shapes was not correctly accounted for in the calculations. Empirical adjustments of the yrast line, to simulate the spin-induced enhancement of the level density, provided good descriptions of the experimental spectra. The required enhancement of the level density was found to be too large with respect to theoretical expectations [16]. Later it was pointed out that a change of the phase space equivalent to that required by the level-density enhancement can be obtained by considering the nuclear deformation as a frozen degree of freedom during the particle decay [35]. Particle decay with frozen deformations follows earlier suggestions on the compound nucleus decay [36,37] and fits well into recent investigation son the importance of the shape degrees of freedom in the dynamics of fission [38]. In a work on the decay of ^{59}Cu nuclei [14], it has been shown that the discrepancies between calculations and experimental data can be removed by considering the shape degrees of freedom frozen during the particle emission until the lifetime of the emitting system becomes comparable with the computed minimum time required for shape changes in nuclei $\tau_{shape} \sim 2\times10^{-21}$ s. The lifetime of the decaying system can be estimated in the statistical model as $\tau_{stat} = \Gamma_{tot}/\hbar$. The statistical lifetime has been estimated for different states (E_x, J) in ^{40}Ca. It results that the time for relaxing the shape degree of freedom approaches the statistical lifetime for excitation energies of the order of $E_x \sim 40$ MeV. This means that, following the frozen deformation suggestion, the spin effects should be important in ^{40}Ca for particle emission in which the parent deformed nucleus lies at an excitation energy larger than 40 MeV.

For a fixed change of the deformation at a given angular momentum (i.e., lowering the yrast line or freezing the emitter deformation), the relative induced modification on the phase space decreases by increasing the excitation energy above the yrast line. As a result, the sensitivity of the calculation to this angular momentum induced effects depend on a few coincident situations: (1) strongly deformed states are populated in the compound nucleus; (2) alpha particles are emitted from the deformed states; (3) the alpha particles sample the region of phase-space close to the yrast line; and (4) the multiplicity of the above "sensitive" alpha particles is comparable to the multiplicity of "insensitive" alpha particles (i.e., those emitted from lower deformed states and/or sampling phase-space regions not close to the yrast line at high spin).

As can be easily understood from the above list of conditions, the entrance channel plays an essential role in making the alpha-particle decay from a given compound nucleus a sensitive probe to the spin-related effects. Generally it is expected that if the maximum angular momentum for fusion is saturated because of the vanishing of the fission barrier, any further increase of the bombarding energy should produce a decrease of the spin sensitivity of alpha emission.

As a definitive test for the low sensitivity of the computed alpha-particle spectra to the angular momentum dependent modifications of the phase space, we present in Fig. 12 an example of spectra in the extreme case of using in the calculation the yrast line for spherical nucleus. The striking result is that the disagreement in the high-energy part of the spectra is more pronounced for the calculation at 60 MeV bombarding energy than at 130 MeV. It means that at the lower bombarding energy, despite the average spin of the compound nucleus being only $\langle J \rangle = 17\hbar$, the calculation is more sensitive to the spin dependence of phase space, and the Sierk yrast line is needed to fit the experiment. At an excitation energy of $E_x = 94$ MeV, the average spin of the emitter is increased up to $\langle J \rangle = 24\hbar$, but the alpha decay from ^{40}Ca feels only very little the underlying yrast line. This means that in this case one or more conditions for the sensitivity to spin effects discussed above are not satisfied. The scarce sensitivity to spin effects of the alpha-particle emission at 130 MeV bombarding energy makes meaningless in the present case any test on the frozen deformation hypothesis in particle decay from light compound nuclei.

To show the sensitivity of alpha emission to the angular momentum coordinate itself, standard calculations were also performed changing the maximum angular momentum for the fusion. These results are reported in Fig. 13. It appears that a change of J_{max} from $27\hbar$ to $35\hbar$ produces important effects: the average energy of the to-

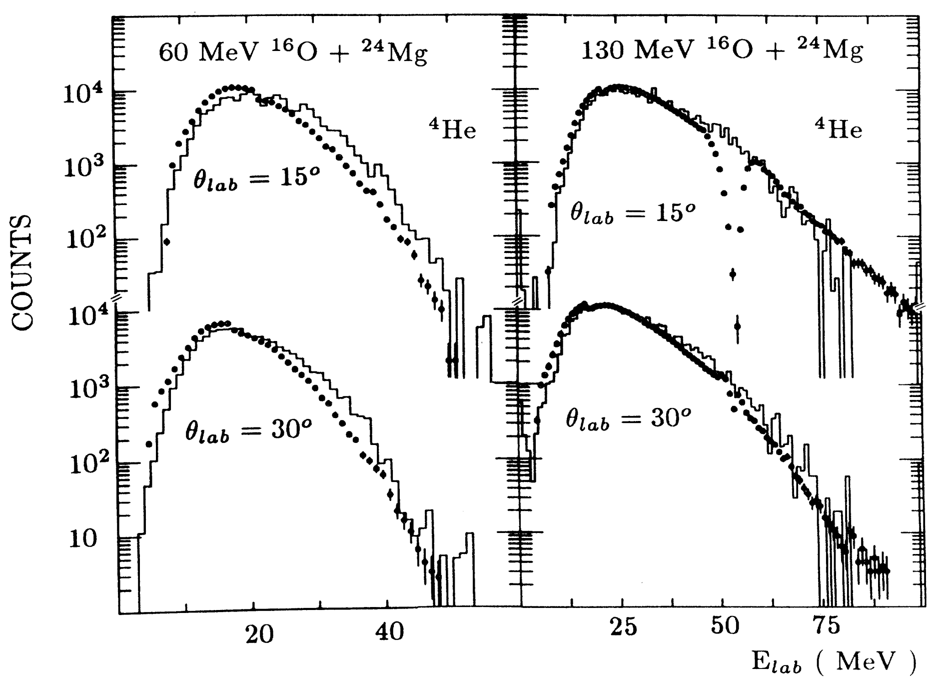

FIG. 12. Comparison between experimental alpha-particle spectra and results from standard statistical model calculation using the yrast line for spherical nuclei.

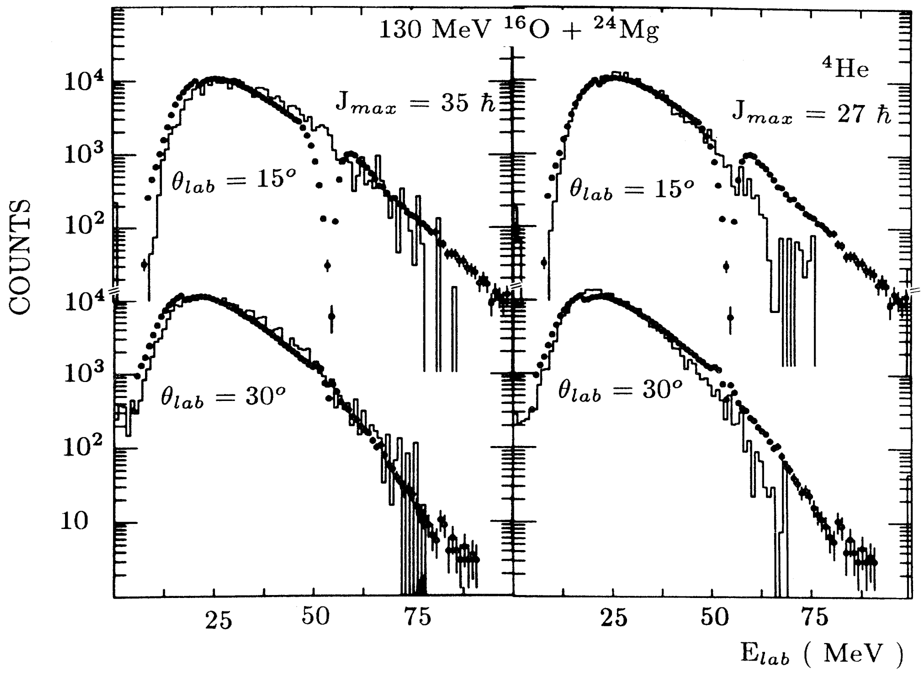

FIG. 13. Comparison between experimental alpha-particle spectra and results from standard statistical model calculation using the Sierk yrast line and different values for the maximum angular momentum.

tal alpha-particle spectrum is slightly higher and the yield of energetic particles is enhanced. It results in a better description of the high-energy part of the spectra at expenses of the low-energy portion. It has to be stressed that this is more effective at the most forward detection angle as could be expected from the semiclassical correlation between angular momentum and emission angle [39].

VI. CONCLUSIONS

We have studied in this work the deexcitation of hot compound ^{40}Ca nuclei formed in the fusion of $^{16}O+^{24}Mg$ at 130 MeV bombarding energy. From an experimental point of view, the present work offers a further proof of the difficulties of isolating compound nucleus decay from the products of two-body reactions. The compound nucleus decay can be tagged in the present case only detecting directly the evaporation residues. Proton and alpha-particle spectra have been compared with the results of Monte Carlo statistical model calculations with standard level-density parametrization, yrast lines, and spherical transmission coefficients.

The analysis of the proton spectra demonstrates that the level density of ^{40}Ca at excitation energies up to $\langle E_{th}/A\rangle \sim 1.7$ MeV is described by the standard Fermi-gas formalism and level-density parameter $a_{eff}=A/8$ MeV^{-1}. This sets a low excitation energy limit, consistent with the current theories, for the transition to the Fermi-gas value of the level-density parameter in light nuclei.

As far as the alpha-particle spectra are concerned, the shape exhibits, at this excitation energy, a reduced sensitivity to angular momentum induced deformations, despite the fact that high spin states are populated in the compound nucleus. This effect has been discussed as evidence for the role of the entrance channel. An important test of the model calculations has been performed also by selecting high spin states in the compound nucleus by requiring multiple alpha-particle coincidences.

Statistical model calculations tend to underestimate the yield of low-energy particles in proton and alpha-particle energy spectra. This last point has been taken in the past as a signature for a barrier lowering due to angular momentum induced deformations [10,11] or for dynamical effects (collective compression-expansion modes) in the hot nucleus [6]. Radial expansion of the hot ^{40}Ca has been predicted by time-dependent Hartree-Fock calculations in the range of temperature encountered at the top of the deexcitation cascade in this work [40]. Model calculations show that the part of the spectra originating from the top of the decay chain is rather small (of the order of 20%), so that the signature of radial expansion might be masked by the decays from nuclei at lower excitation energy. As a further caution, we note that the low-energy part of the spectra can also be tuned in the calculations changing the spin distribution of the initial compound nucleus or modeling the level density at low excitation energies by inserting discrete levels. It is therefore mandatory to isolate experimentally the emission from the first step of the cascade to check qualitatively and quantitatively the predicted thermal expansion of the hot ^{40}Ca compound nucleus and to test the validity of the statistical model prediction with improved accuracy.

[1] See, e.g., in *Proceedings of the Texas A&M Symposium on Hot Nuclei,* College Station, Texas, 1987, edited by S. Shlomo, R. P. Schmitt, and J. B. Notowitz (World Scientific, Singapore, 1987), and references therein.
[2] J. Galin *et al.*, in *Proceedings of the ACS Symposium on Nuclear Dynamics and Nuclear Disassembly,* Dallas, 1989, edited by J. B. Notowitz (World Scientific, Singapore, 1989), p. 320, and references therein.
[3] E. Suraud, Ch. Gregoire, and B. Tamain, Prog. Nucl. Part. Sci. **23**, 357 (1989).
[4] G. Nebbia *et al.*, Phys. Lett. B **176**, 20 (1986).
[5] K. Hagel *et al.*, Nucl. Phys. **A486**, 429 (1988).
[6] M. Gonin *et al.*, Phys. Lett. B **217**, 406 (1989); Phys. Rev. C **42**, 2125 (1990).
[7] P. F. Bortignon and C. Dasso, Phys. Lett. B **189**, 381 (1987), and references therein.
[8] A. Bracco, F. Camera, J. J. Gaardhoie, B. Herskind, and M. Pignanelli, Nucl. Phys. **A519**, 47 (1990).
[9] See, for example, *Proceedings of the International Symposium on Heavy Ion Physics and Nuclear Astrophysical Problems,* Tokyo, 1988, edited by S. Kubono, H. Ishihara, and T. Nomura (World Scientific, Singapore, 1989), and references therein.
[10] Z. Majka, M. E. Brandan, D. Fabris, K. Hagel, A. Menchacha-Rocha, J. B. Natowitz, G. Nebbia, G. Prete, and G. Viesti, Phys. Rev. C **35**, 2125 (1987); G. Viesti, B. Fornal, D. Fabris, K. Hagel, J. B. Natowitz, G. Nebbia, G. Prete, and F. Trotti, *ibid.* **38**, 2640 (1988); B. Fornal *et al.*, *ibid.* **41**, 127 (1990), and references therein.
[11] M. Kaplan *et al.*, in *Proceedings of the Texas A&M Symposium on Hot Nuclei* [1], p. 115, and references therein.
[12] S. Cohen, F. Plasil, and W. Swiatecki, Ann. Phys. **82**, 557 (1974).
[13] F. Puhlhofer, Nucl. Phys. **A280**, 267 (1977).
[14] B. Fornal *et al.*, Phys. Lett. B **255**, 325 (1991).
[15] J. R. Huizenga, A. N. Behkami, I. M. Govil, W. U. Schroeder, and J. Toke, Phys. Rev. C **40**, 668 (1989).
[16] W. E. Ormand *et al.*, Phys. Rev. C **40**, 1510 (1989); B. Lauritzen and G. Bertsch, *ibid.* **40**, 2412 (1989), and references therein.
[17] Y. Chan, M. Murphy, G. R. Stokstad, I. Tserruya, S. Ward, and A. Budzanowski, Phys. Rev. C **27**, 447 (1983).
[18] P. Corvisiero, M. Anghinolfi, L. Z. Dzhilavyan, G. Gervino, L. Grosso, G. Ricco, M. Sanzone, M. Taiuti, and A. Zucchiatti, Nucl. Instrum. Methods A **294**, 478 (1990).
[19] B. A. Harmon, S. T. Thornton, D. Shapira, J. Gomez del Campo, and M. Beckerman, Phys. Rev C **34**, 552 (1986).
[20] B. Fornal *et al.*, Z. Phys. A **340**, 59 (1991).
[21] See, for example, R. G. Stokstad, in *Treatise on Heavy-Ion Science,* edited by D. A. Bromley (Plenum, New York, 1985), Vol. 3, p. 83, and references therein.
[22] R. K. Choudhury, P. L. Gonthier, K. Hagel, M. N. Namboodiri, J. B. Natowitz, L. Adler, S. Simon, S. Kniffen, and G. Berkowitz, Phys. Lett. **143B**, 74 (1984).
[23] W. D. Myers, *Droplet Model of the Atomic Nucleus* (Plenum, New York, 1977).
[24] D. Wilmore and P. E. Hodgson, Nucl. Phys. **55**, 673 (1964); P. E. Hodgson, Annu. Rev. Nucl. Sci. **17**, 1 (1967).
[25] F. G. Perey, Phys. Rev. **131**, 745 (1963).
[26] J. R. Huizenga and G. Igo, Nucl. Phys. **29**, 462 (1961).
[27] D. W. Lang, Nucl. Phys. **77**, 545 (1966).
[28] W. Dilg, W. Schantl, H. Vonach, and M. Uhl, Nucl. Phys. **A217**, 269 (1973).
[29] W. D. Myers and W. J. Swiatecki, Nucl. Phys. **81**, 1 (1966).
[30] A. J. Sierk, Phys. Rev. C **33**, 2039 (1986).
[31] M. Kicinska-Habior, K. A. Snover, J. A. Behr, G. Feldman, C. A. Gosset, and J. H. Gundlach, Phys. Rev. C **41**, 2075 (1990).
[32] A. K. Kerman and S. Levit, Phys. Rev. C **24**, 1029 (1981); B. Lauritzen, G. Puddu, P. F. Bortignon, and R. A. Broglia, Phys. Lett. B **246**, 329 (1990).
[33] S. Shlomo, private communication.
[34] C. Gregoire, T. T. S. Kuo, and D. B. Stout, Nucl. Phys. **A530**, 94 (1991).
[35] B. Fornal, G. Viesti, G. Nebbia, G. Prete, and J. B. Natowitz, Phys. Rev. C **40**, 664 (1989).
[36] M. Blann, Phys. Rev. C **21**, 1770 (1980).
[37] M. Blann and T. T. Komoto, Phys. Rev. C **24**, 426 (1981).
[38] D. J. Hinde, D. Hilsher, and H. Rossner, Nucl. Phys. **A502**, 497 (1989).
[39] T. Ericson and V. Strutinski, Nucl. Phys. **8**, 284 (1958); **9**, 689 (1959).
[40] J. Okolowicz, M. Ploszajczak, S. Drozdz, and E. Caurier, Nucl. Phys. **A501**, 289 (1989).