Preequilibrium processes in the fusion of ^{12}C with ^{103}Rh up to 20 MeV/nucleon

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(Received 13 June 1996)

We have measured the excitation functions of several reactions occurring in the fusion of ^{12}C with ^{103}Rh at incident energies up to about 230 MeV. The data can be satisfactorily reproduced by considering the preequilibrium emission of particles during the thermalization of the composite nucleus. The energy evolution of the mean-field interaction is also discussed. [S0556-2813(96)02512-5]

PACS number(s): 25.70.Gh, 25.70.Jj

I. INTRODUCTION

The analysis of a large number of excitation functions of reactions occurring in the fusion of ^{12}C and ^{16}O with heavy nuclei has shown that, even at incident energies only slightly higher than the Coulomb barrier, preequilibrium nucleons are emitted during the thermalization of the composite nucleus [1,2]. The small but measurable cross section for formation of some of the heavier residues (equal to about one or less than one percent of the reaction cross section) cannot be accounted for, in the incident energy range studied, by considering only evaporation from an equilibrated compound nucleus and points to the emission of nucleons with energies substantially higher than those expected at equilibrium. The rate of emission of these nucleons depends sensitively on the mean-field interaction between the projectile and the target [2]. This determines the initial energy distribution of the nucleons in the projectile and the target nuclei, which start a cascade of nucleon-nucleon interactions as soon as the two nuclei touch. The investigation of higher-energy data is expected to throw new light on this subject and to allow one to study the evolution of the mean-field interaction with increasing energy [3]. This is done in this paper in which we discuss the results we have recently obtained in a study of the interaction of ^{12}C with ^{103}Rh from an incident energy of about 40 MeV (the two-ion Coulomb barrier) up to about 230 MeV.

II. EXPERIMENTAL DETAILS AND RESULTS

As in many previous works studying the interaction of carbon with nuclei [1,2,4–19], the activation technique was employed, and the γ activities induced by ^{12}C irradiation of ^{103}Rh microfoils and aluminium catchers were measured at increasing times after the end of bombardment. The residues were identified by their characteristic γ lines and their half-lives [20]. The data were obtained in three different stages.

First, a series of irradiations was performed at the Laboratorio Nazionale del Sud at Catania in Italy with ^{12}C beams of the MP Tandem, at energies varying from about 39 to about 98 MeV, in 5 MeV steps, using 310 $\mu g/cm^2$ ^{103}Rh microfoils and 1800 $\mu g/cm^2$ aluminium catchers. The charge state of the ^{12}C ions varied with increasing energy from 4^+ to 6^+, the irradiation time was about 1 h at each energy and the beam current about 60 e nA.

Second, a foil-stack irradiation was performed at the National Accelerator Centre at Faure in South Africa, using the newly developed ^{12}C beam of the Separated Sector Cyclotron Facility. A stack of 9 foils of ^{103}Rh, 310 $\mu g/cm^2$ thick, mounted on a 1.5 μm thick Mylar backing, interspaced with 1730 $\mu g/cm^2$ aluminium absorbers and 3730 $\mu g/cm^2$ aluminium degraders was bombarded for about 1 h with a 151.3 MeV $^{12}C^{4+}$ beam at a beam current of about 40 e nA. The ^{12}C energy on the rhodium foils decreased through the stack from 151.3 to about 95.4 MeV, in energy steps varying from about 5.8 to 7.6 MeV.

Finally, a second foil-stack irradiation was also performed at the National Accelerator Centre by bombarding a stack consisting of 16 rhodium foils identical to the above-mentioned 2340 $\mu g/cm^2$ aluminium catchers and 3730 $\mu g/cm^2$ aluminium degraders with a 225.8 MeV $^{12}C^{4+}$ beam of intensity of about 15 e nA. In this case the ^{12}C energy on the rhodium foils decreased through the stack from 225.8 to about 138.5 MeV in energy steps varying from about 5 to 7 MeV.

The rhodium foils were from Goodfellow Metals Ltd., U.K., and their thickness was specified to within an uncertainty of about 20%. Considering the various sources of errors, including the uncertainty in target thickness, in the beam fluence measurement, the Ge(Hp) detector efficiency,

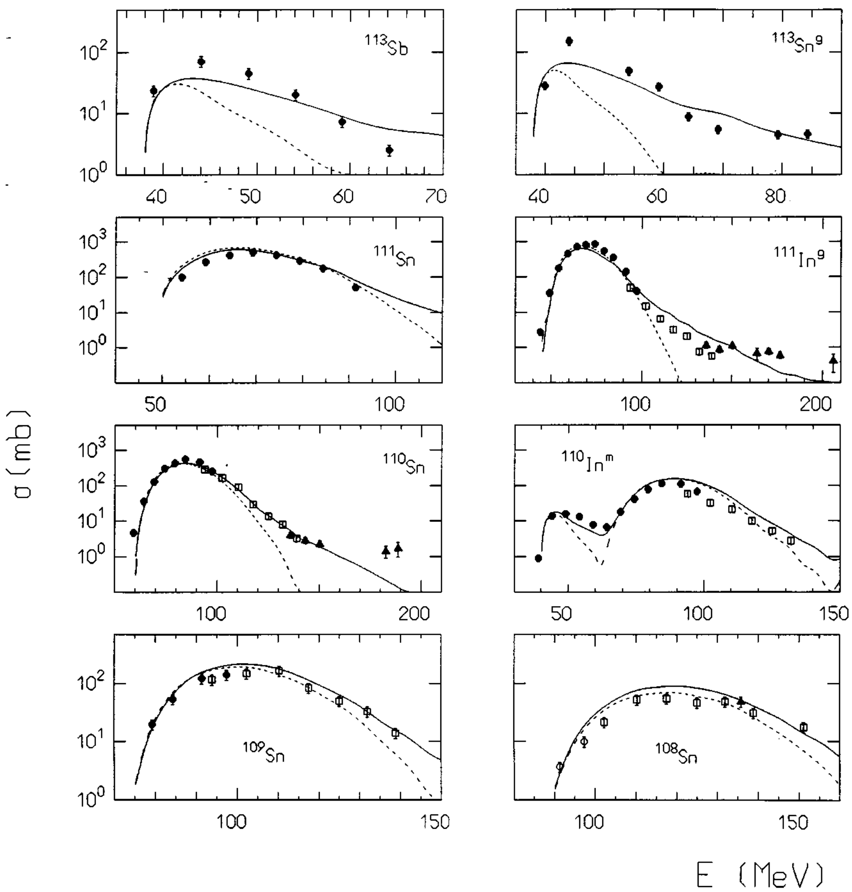

FIG. 1. Excitation functions for production of the residues shown. The full circles, the open squares, and the full triangles give the experimental cross sections measured in the three stages described in the text. The dashed lines give the calculated excitation functions not considering preequilibrium emission and the full lines those obtained considering preequilibrium emission with the *low-energy approximation* for the mean-field interaction.

the counting efficiency due to electronics dead time and the statistical errors in evaluating the γ-line intensity and the background subtraction, the uncertainty in the cross sections reported later is estimated to be less than 30% ($\approx$25% random and 5% systematic).

We chose ^{103}Rh as a target instead of a heavier nucleus with the purpose of extending our previous studies of the interaction of ^{12}C with nuclei to higher incident energies without having a high probability for fission in the exit channel. Rhodium ensures that the cross section for decay by fission is small compared to the total fusion cross section, even at the highest energies we considered.

Six of the residues we observed are isotopes of Sb and Sn produced in the decay of ^{115}Sb after its formation in the fusion reaction. The indium isotopes with mass below 111 may be produced by the incomplete fusion of a ^{8}Be fragment, however the two heavier isotopes we observe (^{111}In^g and ^{110}In^m) are also mainly produced in the complete fusion since the intermediate composite nucleus formed in the incomplete fusion is too excited to emit only γ rays or just a neutron and γ rays. The excitation functions of Sb and Sn isotopes and these two In isotopes are shown in Fig. 1. Most of these residues are produced cumulatively, that is both directly in the interaction of ^{12}C with ^{103}Rh and by decay of precursors also formed in the reaction. Most of the cross sections given in Table I for their formation, calculated as discussed by Cavinato *et al.* [2], are cumulative cross sections, i.e., the sum of the independent cross sections for production of the residue as well as its precursors.

III. THEORETICAL ANALYSIS

The analysis of the excitation functions shown in Fig. 1, using the theory discussed in [1,2], allowed us to deduce the values of the fusion cross section σ_{CF}, which is shown in Fig. 2 as a function of the incident energy, together with the reaction cross section σ_R estimated by means of the semiclassical expression using the parameters given by Bass [21]. In a sharp cutoff approximation the corresponding critical angular momentum for fusion is about $50\hbar$. This value agrees very well with that evaluated with the critical angular momentum model [22–24]. Starting from about 60 MeV incident energy σ_{CF} becomes smaller than σ_R due to the competing incomplete fusion reactions.

The dashed curves in Fig. 1 show the results of calcula-

TABLE I. Cumulative cross section for production of the fusion residues which have been detected.

Residue	Contribution to cumulative residue production
^{113}Sb	^{113}Sb
^{113}Sn^g	^{113}Sn^g+0.910^{113}Sn^m+0.982^{113}Sb
^{111}Sn	^{111}Sn+1.037^{111}Sb+1.046(^{111}Te+^{111}I)
^{111}In^g	^{111}In^g+1.009^{111}Sn+1.009^{111}Sb+1.002^{111}In^m
^{110}Sn	^{110}Sn+1.002^{110}Sb
^{110}In^m	Independent production
^{109}Sn	^{109}Sn+1.016^{109}Sb
^{108}Sn	^{108}Sn+1.011^{108}Sb

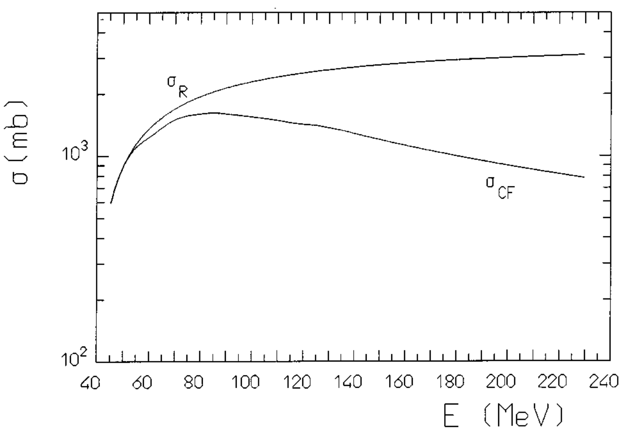

FIG. 2. Reaction and complete fusion cross sections for the interaction of ^{12}C with ^{103}Rh.

tions made by assuming that all the fusions lead to an equilibrated compound nucleus with full excitation energy. The parameters used in these calculations are the experimental binding energies [25] when known, or those evaluated with the Myers-Swiatecki formula [26], the Nemirovski-Adamchuck pairing energies [27], and the semiclassical inverse cross sections [28,29] calculated with parameters chosen to reproduce with fair accuracy those calculated with the optical model (the semiclassical expressions are used to calculate analytical expressions of the compound nucleus decay rates). The level density parameter was taken to be $a=A/8$ MeV^{-1} for all nuclei in the evaporation chain, even though several of these nuclei are in the $Z=50$ magic shell region, because the results of the calculation were found not to change appreciably when a shell correction at low excitation energies is used. Angular-momentum effects were taken into account as discussed by Vergani *et al.* [1]

The results of the calculation do not appreciably change using a values slightly different from those given above, such as $a=A/7$ or $a=A/9$ MeV^{-1}, however one must take into account that the lowest-energy discrete levels of the residual nuclei may be not accurately *counted* by the level density expression and this may slightly affect our results.

The results of the calculations also depend on the energies of the yrast states, thus on the moment of inertia of the residual nucleus for which we initially used the values predicted by the rotating charged liquid-drop model (RCLDM) [30]. This, however, led to a systematic disagreement between the calculated and the experimental excitation functions in all the cases considered, which could be reduced by using moments of inertia about 40% higher than those predicted by the RCLDM. With this increase, the energies of the yrast states become approximately equal to the rotational energies of a spherical nucleus with reduced radius $r_0 \approx 1.55$ fm. Even so, however, while some of the excitation functions were reproduced reasonably well, in other cases the calculation completely failed to reproduce the data. The agreement between the data and the theory is particularly poor in the case of the two heavier residues we observed, namely ^{113}Sb and ^{113}Sn^g, for which the calculated cross section above about 60 MeV is more than 1 order of magnitude smaller than the measured one, and in the tail of the excitation functions of ^{111}In^g and ^{110}Sn.

The calculation was therefore repeated by also considering the emission of preequilibrium nucleons during the thermalization cascade of nucleon-nucleon interactions, through which the orderly translational motion of the nucleons of the two fusing ions transforms into chaotic thermal motion of the nucleons of the compound nucleus. As in the case of the fusion of ^{12}C with the heavier nuclei we have already investigated [1,2], we assumed that when the projectile and target nucleons start to interact, the relative translational momentum of the two ions, slowed down by the Coulomb repulsion, is greatly reduced, and a sizeable fraction of the energy is *frozen* as collective deformation energy. To take this effect into account, we used an effective reaction Q value, $Q_{\text{eff}} \approx -B$, where B is the two-ion Coulomb barrier at contact, and in evaluating the initial nucleon energy distributions by coupling the internal momentum of each nucleon in the center of mass of its own ion with the translational momentum per nucleon of the ion in the center of mass of the two-ion system, we used the translational momenta of the slowed-down ions [2]. This is the *low-energy approximation* for describing the mean-field interaction. At the end of the thermalization, the collective deformation energy transforms into chaotic thermal energy of the nucleons of the equilibrated nucleus left. The A and Z distribution of the equilibrated nuclei after thermalization was calculated with a Monte Carlo code, using the probabilities of emitting a particle (a neutron, proton, deuteron, triton, ^{3}He, or an α particle) in small time intervals along the thermalization cascade, calculated increasing time by solving a set of coupled Boltzmann master equations [31]. The results of this calculation (which in the case of ^{110}In^m also include a small contribution of the ^{8}Be incomplete fusion) are given by the full lines in Fig. 1 and show that, for incident energies below about 150 MeV, consideration of the preequilibrium particle emission eliminates most of the disagreement between data and theory previously found even if the predicted total number of preequilibrium particles, shown in Fig. 3, is rather small.

These results show that the theoretical model we previously used for describing the fusion of ^{12}C with heavy nuclei also successfully describes our new data obtained for a much lighter target nucleus and extending to higher incident energies. On the other hand, above about 150 MeV the model fails to reproduce the data accurately, as illustrated by the ^{111}In^g and ^{110}Sn excitation functions. This is not surprising, since with increasing energy the mean-field interaction is expected to change, due to a considerable reduction of the importance of Coulomb effects. At sufficiently high energies the Coulomb repulsion is steadily overcome and the two ions merge in a common composite nucleus regaining the kinetic energy that was transformed into potential energy. The nucleons of the two ions may even gain additional energy because the Fermi energy of the composite nucleus is greater than that of both the projectile and the target according to predictions of the shell model and the liquid-drop model with a surface energy correction. This effect is discussed by Brusati *et al.* [3], who showed that it must be considered at incident energies above about 20 MeV/nucleon when evaluating the energy distribution of the nucleons of the composite nucleus at the beginning of the thermalization cascade of

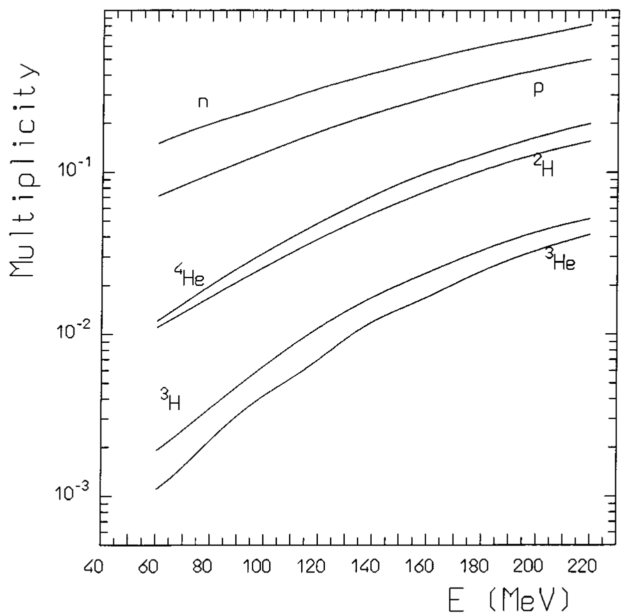

FIG. 3. Predicted number of preequilibrium particles as a function of the incident ^{12}C energy. Below about 130 MeV the values shown are those predicted with the *low-energy approximation* for the mean-field interaction, while above about 170 MeV are shown those predicted with the *intermediate-energy approximation.* In between the values shown were obtained by interpolation.

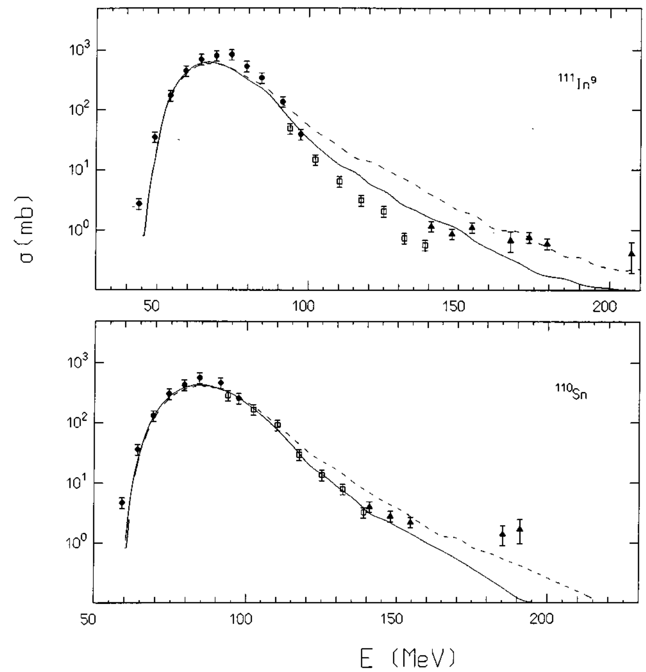

FIG. 4. Excitation functions for production of ^{111}In^g and ^{110}Sn. The full and the dashed lines give the theoretical predictions using, respectively, the *low-* and the *intermediate-energy approximation* for the mean-field interaction.

nucleon-nucleon interactions. Between an incident energy of about 12.5 MeV/nucleon and about 20 MeV/nucleon, where the low-energy assumptions do not seem to allow an accurate reproduction of the data, an intermediate mean-field interaction between those corresponding to these two well-established theoretical approximations should presumably be used and therefore we have assumed, as a calculation prescription, that, in evaluating the nucleon energy distribution at the beginning of the thermalization cascade, one must neither reduce the total energy by the Coulomb repulsion nor increase the nucleon energy as they merge into the composite nucleus. This is the *intermediate-energy approximation* for the mean-field interaction. The excitation functions for the production of ^{111}In^g and ^{110}Sn calculated in such a way are shown in Fig. 4, and are in considerably better agreement with the data between about 150 and 230 MeV.

IV. CONCLUSIONS

To summarize, we have shown in this work that, by assuming a reasonable change with incident energy of the mean-field interaction, one is able to predict accurately the strength of preequilibrium emission in the fusion of ^{12}C with ^{103}Rh. We have also shown that to understand the reaction mechanism one needs to analyze a large set of data since some experimental results are rather insensitive to the different processes which may occur. Finally, in order to reveal the quite small effect of preequilibrium emission at low incident energies, one needs to measure accurately cross sections which are 3 orders of magnitude smaller than the total reaction cross section. This is easily done by means of the activation technique, which, in addition, provides the comprehensive information which we have shown to be necessary to draw sensible conclusions.

[1] P. Vergani, E. Gadioli, E. Vaciago, E. Fabrici, E. Gadioli Erba, M. Galmarini, G. Ciavola, and C. Marchetta, Phys. Rev. C **48**, 1815 (1993).

[2] M. Cavinato, E. Fabrici, E. Gadioli, E. Gadioli Erba, P. Vergani, M. Crippa, G. Colombo, I. Redaelli, and M. Ripamonti, Phys. Rev. C **52**, 2577 (1995).

[3] C. Brusati, M. Cavinato, E. Fabrici, E. Gadioli, and E. Gadioli Erba, Z. Phys. A **353**, 57 (1995).

[4] T. Darrah Thomas, G. E. Gordon, R. M. Latimer, and G. T. Seaborg, Phys. Rev. **126**, 1805 (1962).

[5] J. M. Alexander and G. N. Simonoff, Phys. Rev. **133**, 93 (1964).

[6] G. N. Simonoff and J. M. Alexander, Phys. Rev. **133**, 104 (1964).

[7] R. Bimbot, D. Gardès, and M. F. Rivet, Nucl. Phys. **A189**, 193 (1972).

[8] T. Lund, D. Molzahan, B. Bergesen, E. Hagebo, I. R. Haldorsen, and C. Richard-Serre, Z. Phys. A **306**, 41 (1982).

[9] H. Kudo, K. J. Moody, and G. T. Seaborg, Phys. Rev. C **30**, 1561 (1984).

[10] R. Kossakowski, J. Jastrzebski, P. Rymuza, W. Skulski, A. Gizon, S. André, J. Genevey, J. Gizon, and V. Barci, Phys. Rev. C **32**, 1612 (1985).

[11] R. Kossakowski, S. André, J. Genevey, A. Gizon, V. Barci, D.

Barnéoud, A. Charvet, C. Foin, and J. Salicio, Phys. Rev. C **33**, 1514 (1985).
[12] S. Y. Chao, Y. H. Chung, N. T. Porile, and D. J. Morissey, Phys. Rev. C **36**, 2349 (1987).
[13] S. Y. Chao, N. T. Porile, and D. J. Morissey, Phys. Rev. C **39**, 2227 (1989).
[14] Y. H. Chung, S. Y. Chao, and N. T. Porile, Nucl. Phys. **A533**, 170 (1991).
[15] D. J. Parker, P. Vergani, E. Gadioli, J. J. Hogan, F. Vettore, E. Gadioli Erba, E. Fabrici, and M. Galmarini, Phys. Rev. C **44**, 1528 (1991).
[16] Li Wenxin, Yin Xinmin, Luo Qingzheng, Zhao Lili, Sun Tongyu, and Wu Dingqing, Phys. Rev. C **46**, 1538 (1992).
[17] B. S. Tomar, A. Goswami, A. V. R. Reddy, S. K. Das, P. P. Burte, S. B. Manohar, and S. Prakash, Z. Phys. A **343**, 223 (1992).
[18] J. P. Whitfield and N. T. Porile, Phys. Rev. C **47**, 1636 (1993).
[19] M. Crippa, E. Gadioli, P. Vergani, G. Ciavola, C. Marchetta, and M. Bonardi, Z. Phys. A **350**, 121 (1994).
[20] E. Browne and R. B. Firestone, *Table of Radioactive Isotopes* (Wiley, New York, 1986).
[21] R. Bass, *Nuclear Reactions with Heavy Ions* (Springer-Verlag, Berlin, 1980), p. 110.
[22] J. Wilczyński, Nucl. Phys. **A216**, 386 (1973).
[23] J. R. Birkelund, L. E. Tubbs, J. R. Huizenga, J. N. De, and D. Sperber, Phys. Rep. **56**, 107 (1979).
[24] W. W. Wilcke, J. R. Birkelund, H. J. Wollersheim, A. D. Hoover, J. R. Huizenga, W. U. Schröder, and L. E. Tubbs, At. Data Nucl. Data Tables **25**, 389 (1980).
[25] G. Audi and A. H. Wapstra, Nucl. Phys. **A565**, 1 (1993).
[26] W. D. Myers and W. J. Swiatecki, Nucl. Phys. **81**, 1 (1966); Ark. Fys. **36**, 343 (1967).
[27] P. E. Nemirovski and Yu. V. Adamchuck, Nucl. Phys. **39**, 551 (1962).
[28] I. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. **116**, 683 (1959).
[29] E. Gadioli, E. Gadioli Erba, and J. J. Hogan, Phys. Rev. C **16**, 1404 (1977).
[30] A. J. Sierk, Phys. Rev. C **33**, 2039 (1986).
[31] M. Cavinato, E. Fabrici, E. Gadioli, E. Gadioli Erba, and E. Galbiati, Phys. Lett. B **382**, 1 (1996).