Selective Parity Transitions and Dinuclear Orbiting of $^{12}C + ^{24}Mg$

W. Dünnweber, A. Glaesner,[a] W. Hering, D. Konnerth, R.Ritzka,[a] and W. Trombik
Sektion Physik, Universität München, 8046 Garching, West Germany

and

J. Czakański and W. Zipper
Institute of Physics, Silesian University, 40-007 Katowice, Poland
(Received 8 February 1988)

In a spectroscopic study of the backward-angle yield from $^{12}C + ^{24}Mg$ at 3–4 times the Coulomb barrier, we find a strong preference for natural parity transitions in the excitation of close-to-yrast rotational bands. This selectivity is in strong quantitative disagreement with Hauser-Feshbach calculations for a compound-nuclear reaction and provides evidence for the conservation of the dinuclear parentage.

PACS numbers: 25.70.Lm, 25.70.Gh

"Orbiting" light heavy-ion systems are intriguing candidates for the study of double nuclei. The isotropic differential cross section $d\sigma/d\theta$ at large backward angles, which characterizes the orbiting-reaction component, has been observed for several systems with mass numbers $A_1 = 12$–16 and $A_2 = 20$–48 at energies of a few times the Coulomb barrier.[1-7] This type of angular distribution, together with the strong damping of the energy in the relative motion, is suggestive of a double nucleus clinging together for a long time. Indeed, lifetimes deduced from the cross-section fluctuations of $^{12}C + ^{24}Mg$ orbiting-type reactions correspond to mean rotational angles in the range between one-half and one complete revolution.[6]

However, dinuclear orbiting is not easily distinguished from the formation of a compound nucleus. The same type of angular distribution and similar average energies in the exit channels are expected in both cases. Estimates of compound-nuclear cross sections and lifetimes depend sensitively on model parameters. A strong argument against a dominantly compound-nuclear origin of the orbiting component comes from the entrance-channel dependence of the oxygen-to-carbon yield ratio found in a comparative study[4] of $^{16}O + ^{24}Mg$ and $^{12}C + ^{28}Si$. Recently, however, the observation of mass equilibration for $^{32}S + ^{24}Mg$ and a reconsideration of the fission barriers have led to the suspicion that the orbiting yields are generally the result of compound-nuclear decay.[8]

This Letter draws attention to a spectroscopic indicator of the dinuclear character of a heavy-ion reaction, namely, the parity transition, which is called *natural* if the product of the intrinsic parities in a reaction $a + A \rightarrow b + B$ obeys the equation

$$\pi(a)\pi(A)\pi(b)\pi(B) = (-)^l, \qquad (1)$$

and *unnatural* otherwise.[9] The angular momentum transfer $\mathbf{l} = \mathbf{I}_B + \mathbf{I}_b - \mathbf{I}_A - \mathbf{I}_a$ is related to the entrance- and exit-channel orbital angular momenta by $\mathbf{l} = \mathbf{L}_i - \mathbf{L}_f$. In the example of inelastic scattering of spin-zero nuclei exciting only one nucleus, the parity transition is natural if the excited state has natural parity, $\pi = (-)^l$. Angular momentum and parity conservation allow for both parity transitions, but unnatural transitions are forbidden in the case of simple first-order direct interactions.[9-11] Such transitions have been used, therefore, to study deviations from a direct one-step reaction mechanism in light-ion inelastic scattering.[10] In general, if the outgoing wave function is evaluated at the same relative coordinates as the incoming wave function and if the interaction is a simple function of the intrinsic and relative coordinates, only natural parity transitions are allowed.[10,11] In a compound reaction, both parity transitions are equally allowed and are generally observed. Close to the beam axis ($\theta < 1/L_f$), unnatural parity transitions are forbidden in any two-body reaction by the conservation laws,[12,13] which are of course incorporated in the Hauser-Feshbach formalism for the compound nucleus.

We have performed a spectroscopic study of large-angle $^{12}C + ^{24}Mg$ scattering. With use of inverse kinematics, ^{12}C targets of 45-$\mu g/cm^2$ density were bombarded with ^{24}Mg beams from the Munich MP tandem accelerator at various energies between 90 and 126 MeV. Energy spectra of $Z = 5$ to 9 products were recorded by means of ΔE-E telescopes consisting of axial-field ionization chambers and position-sensitive Si detectors. The covered angular range from 10° to 20° corresponds to backward angles from $\theta_{c.m.} \approx 135°$ to 155° in the center-of-mass system. With use of two-body kinematics, the energy spectra were transformed to Q-value spectra where the resolution was ≤ 600 keV (FWHM). While only the charge Z was resolved by the heavy-ion telescopes, all prominent narrow-peak structures are found to originate from the $N = Z$ channels.

The Q-value spectra (Fig. 1) show broad bell-shaped gross structure and superimposed narrow peaks which

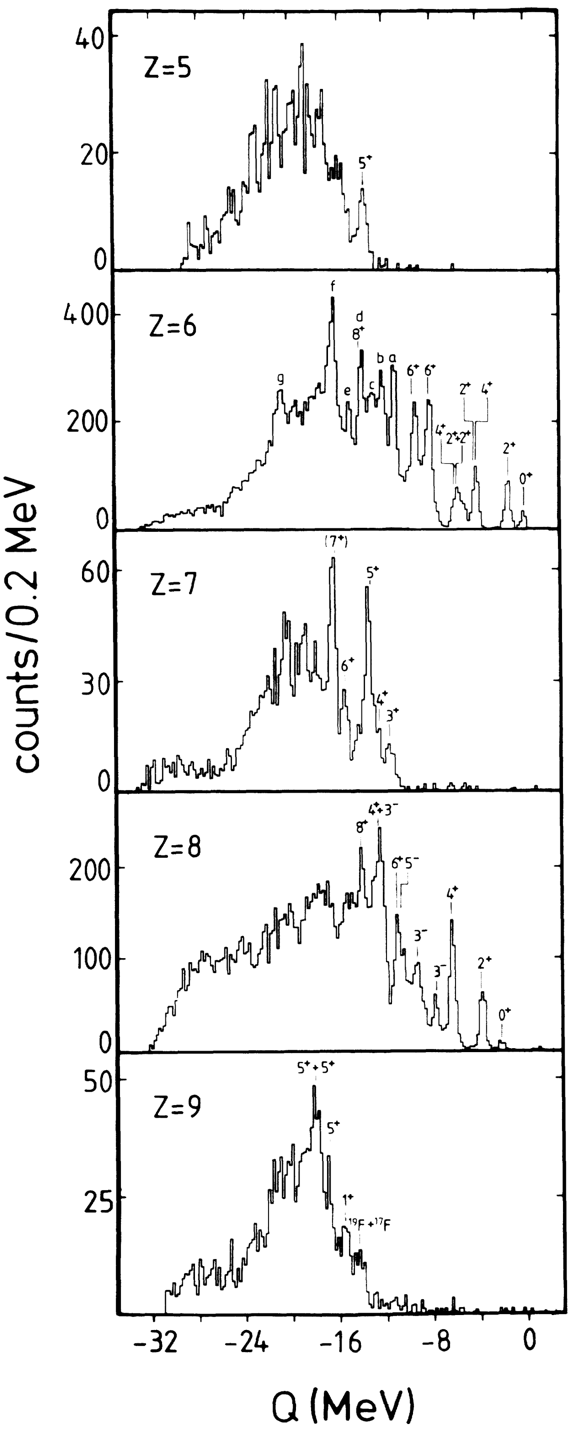

FIG. 1. Q-value spectra for different exit channels from 107-MeV $^{24}Mg+^{12}C$, integrated over $\theta_{c.m.}\approx 135°$ to $155°$. The positions of yrast states or close-to-yrast states of the heavy fragment, coupled to the ground state of the light fragment, are indicated. Peaks a–g are compatible with the positions of clusters of $I=5\hbar-10\hbar$ states of ^{24}Mg (Ref. 14). Sums refer to excitations of both fragments. The Q-integrated cross sections are, from top to bottom, $d\sigma/d\theta=0.6\pm0.1$, 11.0 ± 1.1, 1.0 ± 0.1, 5.6 ± 0.6, and 0.22 ± 0.03 mb/rad.

can be identified with members of low-lying rotational bands up to $|Q|\approx 12$ MeV and, at large $|Q|$, are correlated within our experimental precision of ±0.1 to 0.2 MeV with the positions of large-spin states known[14,15] from fusion reactions. The odd-Z channels have large negative ground-state Q values and allow some unambiguous assignments of low-lying levels.[16]

The visibility of peak structures in the even-Z channels up to $|Q|=20$ to 25 MeV, where the total level densities are extremely high, can be explained by a strong selectivity for states with largest spin at a given excitation energy. In the classical energy and angular momentum balance for damping processes in a light asymmetric system, the energy loss from the relative motion is mainly taken up as rotational energy by the targetlike fragment, which is hence populated in (E_x,I) regions close to the yrast line.[17] Such matching conditions apply, however, also to the emission of clusters from a compound nucleus, where the same type of selectivity can be observed.[18]

A close inspection of the energy spectra (Fig. 1) reveals another selectivity which is rather surprising. Natural-parity states of the heavy fragment are strongly favored in the even-Z channels, as are unnatural-parity states in the odd-Z channels. Particularly striking is the suppression of the (3^+, 5.24 MeV) and (5^+, 7.81 MeV) states of the $K=2$ band of ^{24}Mg as compared to the even-spin members of this band, and the suppression of the 4^+ and the 6^+ states of the ^{22}Na $K=3$ ground-state band. All prominent peaks in the $Z=6$ and 8 channels are consistent with being associated with natural parity transitions.[7] In the odd-Z channels, the prominent even-parity odd-I states of the heavy fragment are coupled to $^{10}B(3^+$, ground state), $^{14}N(1^+$, ground state), and $^{18}F(5^+$, 1.12 MeV), respectively, which are unnatural-parity states as well. Therefore, the total parity transition is natural for the stretched spin configurations where $\pi(b)\pi(B)=(-)^{(I_b+I_B)}$. Hence, the selectivity observed in these channels indicates a combined selectivity for natural parity transitions and for parallel relative spins.

The measured cross sections for the ^{22}Na ground-state band coupled to $^{14}N(1^+)$ are shown in the upper part of Fig. 2. In order to suppress the influence of fluctuations,[6] an average has been performed over three neighboring energies with $\Delta E^i_{c.m.}=333$ keV.

For a quantitative comparison to the expectation for the compound-nuclear case, we have used the Hauser-Feshbach (HF) model,[20] which treats rigorously angular momentum coupling and parity conservation for discrete exit-channel states and which has been found[18] to account well for the decay of sd-shell compound nuclei into clusters of mass numbers up to 16. It has been pointed out[18] that the transition-state model, which provides the generally preferred approach to fission of heavy nuclei, and the HF model become consistent and use the same

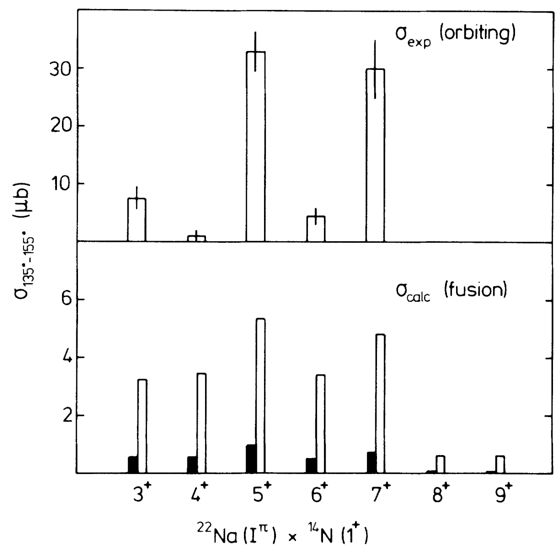

FIG. 2. Top: Measured cross sections $\sigma_{135°-155°} = \int_{135°}^{155°} (d\sigma/d\theta)_{\mathrm{c.m.}} d\theta_{\mathrm{c.m.}}$ averaged over $E^{i}_{\mathrm{c.m.}} = 35.3-36.0$ MeV, for the ^{22}Na ground-state band (Ref. 16) coupled to ^{14}N(1$^+$). Bottom: Fusion cross sections for the same angular range calculated with a universal potential (Ref. 19) and level-density parameter $a = A/7.5$ (full bars) and with the same potential diminished by 2 MeV and $a = A/8.0$ (open bars).

phase space when the saddle-point shape approaches that of two touching spheres, which is expected in the rotating-liquid-drop model for light compound nuclei. The fission barrier of ^{36}Ar is expected to vanish at an angular momentum ($L_{\mathrm{crit}} \approx 30\hbar$)[21] which is well above those values [$L_f = (13-17)\hbar$] where the HF transmission coefficients for ^{14}N + ^{22}Na drop to 0.5. Similar saddle-point shapes are expected in particular for exit-channel states of the same rotational band. Hence, to study their relative intensities, the HF model gives a good formulation of our present understanding of compound-nuclear decay.

The calculations were done with standard parameters, as given in previous work[22] on α and ^{8}Be evaporation from ^{32}S, where good agreement with the experimental results was obtained for a large set of bombarding energies and excited states, including natural and unnatural parity transitions. The transmission coefficients for cluster ($A \geq 4$) decay were taken from the Hill-Wheeler expression for penetration of the real potential barrier[22] with use of various universal potentials.[19,23,24] The entrance-channel transmission coefficients, calculated in the same manner, reproduce the measured total fusion cross section.[25]

The absolute cross sections of the present orbiting-reaction channels are generally underpredicted by the HF calculations by about an order of magnitude (Fig. 2, full bars in lower panel). Similar results were obtained with a double-folding[23] and a proximity[24] potential. While these potentials apply to the (time-reversed) elastic channels, deformations may lead to a decrease of the potential barrier, which governs the transmission coefficients.[22] The absolute cross sections can be enhanced considerably by our decreasing the barrier and also by decreasing the level-density parameter in the competing channels, as is demonstrated in Fig. 2 (open bars). Because of this sensitivity to the exit-channel parameters, conclusions regarding the absolute cross sections must be taken with great care.

However, a clear distinction of orbiting from the compound-nuclear case is made possible by the strongly different odd-even staggering of the relative yields as a function of spin. The preference for positive parity and odd spin I_B, corresponding to natural parity transitions in the case of parallel exit-channel spins with a ^{14}N(1$^+$) ejectile, is only modest in the HF calculations where it is due to the L_f dependence of the transmission coefficients (which favors $\mathbf{L}_f$ parallel to $\mathbf{L}_i$). The relative odd-even differences are found to depend only weakly on the model parameters and to decrease slightly when the barrier height is reduced (Fig. 2). The dramatically different staggering of the measured yield distribution is hence attributed to a selectivity that characterizes a noncompound mechanism.

On the other hand, a selectivity for natural parity transitions is known from direct reactions and has been shown to hold strictly for one-step inelastic scattering with simple interaction operators[9-11] and for one-step transfer in the zero-range approximation.[9] In many-step processes unnatural transitions are in general allowed, but are forbidden if the separation of the intrinsic and relative coordinates is conserved and the interactions can be combined to give a spherical harmonic of a single relative coordinate.[9-11] Both conditions are clearly not met in a compound reaction,[10] but can be approached in dinuclear orbiting.

Complementary aspects of the dinuclear dynamics are revealed by measurements of the spin alignment which, however, do not anticipate the present results. A recent study[26] of a similar system at $\theta = 0°$ has shown that spin-fluctuation modes which mutually dealign both fragments with respect to each other ("bending," "twisting") are not significantly excited, which justifies our assumption of parallel spins. Tilting of the separation axis in the direction $\mathbf{L}_i$ cannot occur at $\theta = 0°$ but is expected to be the main dealigning mode in a relaxed asymmetric system sufficiently away from the beam axis (see, e.g., Refs. 17 and 27). In an angular range close to the present one, our system has been found[28] to be considerably but not fully aligned along the scattering normal, as is typical of heavy-ion damping processes. The average value of the alignment with respect to this quantization axis, $P_{zz} = 0.7 \pm 0.1$, shows that the spin distribution is different from that at $\theta = 0°$ (corresponding to $P_{zz} \approx 0.3$) and does not imply a parity selectivity of the observed size.

To summarize, in the orbiting $^{12}C + ^{24}Mg$ system close-to-yrast states are found to be populated preferentially. In addition, the data show a striking selectivity for natural parity transitions which cannot be reproduced by Hauser-Feshbach calculations for an intermediate mononucleus, but provide evidence for a dinuclear intermediate stage, conserving approximately the entrance-channel separation of the intrinsic and relative coordinates.

This work was supported in part by the German Bundesministerium für Forschung und Technologie and by the Polish Ministry of Science (Contract No. CPBP 01.06).

[a]Present address: Siemens AG, 8000 München, West Germany.

[1]D. Shapira *et al.*, Phys. Lett. **114B**, 111 (1982).

[2]D. Shapira *et al.*, in *Proceedings of the Sixth Adriatic International Conference on Nuclear Physics, Dubrovnik, Yugoslavia, June, 1987,* edited by N. Cindro, R. Caplar, and W. Greiner (World Scientific, Singapore, 1987), p. 55.

[3]B. Shivakumar *et al.*, Phys. Rev. Lett. **57**, 1211 (1986).

[4]A. Ray *et al.*, Phys. Rev. C **31**, 1573 (1985).

[5]R. Ritzka *et al.*, Phys. Rev. C **31**, 133 (1985).

[6]A. Glaesner *et al.*, Phys. Lett. **169B**, 153 (1986).

[7]A. Glaesner *et al.*, to be published.

[8]S. J. Sanders *et al.*, Phys. Rev. Lett. **59**, 2856 (1987).

[9]G. R. Satchler, *Direct Nuclear Reactions* (Oxford Univ. Press, New York, 1983).

[10]W. W. Eidson and J. G. Cramer, Phys. Rev. Lett. **9**, 497 (1962).

[11]N. Austern and J. S. Blair, Ann. Phys. (N.Y.) **33**, 15 (1965).

[12]A. E. Litherland, Can. J. Phys. **39**, 1245 (1961).

[13]G. Murpurgo, Phys. Rev. **131**, 2205 (1963).

[14]L. K. Fifield *et al.*, Phys. Rev. C **8**, 2217 (1973); A. Szanto de Toledo *et al.*, Nucl. Phys. **A315**, 500 (1979).

[15]J. Gomez del Campo *et al.*, Phys. Rev. C **9**, 1258 (1974).

[16]For $Z=7$, the $^{14}N_{g.s.}(1^+) \otimes ^{22}Na(I^+)$ states of the $K=3$ ground-state band ($Q_{gg}=-11.6$ MeV) are identified without ambiguity, except for the (7^+) assignment which relies on the large-spin selectivity of the reaction (cf. Ref. 15).

[17]W. Dünnweber, in *Nuclear Structure and Heavy-Ion Dynamics,* International School of Physics "Enrico Fermi," Course 87, edited by L. Moretto and R. A. Ricci (North-Holland, Amsterdam, 1984), p. 389.

[18]R. G. Stokstad, in *Treatise on Heavy-Ion Science,* edited by D. A. Bromley (Plenum, New York, 1985), Vol. 3, p. 83.

[19]P. R. Christensen and A. Winther, Phys. Lett. **65B**, 19 (1976).

[20]W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952); R. Da Silveira, program HAUFES, Saclay, 1976 (private communication).

[21]M. G. Mustafa *et al.*, Phys. Rev. C **25**, 2524 (1982); A. J. Sierk, Phys. Rev. C **33**, 2039 (1986).

[22]J. Czakanski *et al.*, Phys. Lett. B **199**, 166 (1987).

[23]H. J. Krappe *et al.*, Phys. Rev. C **20**, 992 (1979).

[24]J. Wilczynski and K. Siwek-Wilczynska, Phys. Lett. **55B**, 270 (1975).

[25]K. Daneshvar *et al.*, Phys. Rev. C **25**, 1342 (1982).

[26]A. Ray *et al.*, Phys. Rev. Lett. **57**, 815 (1986).

[27]T. Døssing and J. Randrup, Phys. Lett. **155B**, 333 (1985).

[28]W. Dünnweber *et al.*, in *Proceedings of the Twenty-Fifth International Winter Meeting on Nuclear Physics, Bormio, Italy, 1987,* edited by I. Iori [Ric. Sci. Ed. Permante, Suppl. **56**, 276 (1987)].