Unexpected, Intermediate Structure at High Level Densities in ^{24}Mg

N. Marquardt, R. Volders, C. Cardinal, and J. L'Ecuyer
Laboratoire de Physique Nucléaire, Université de Montréal, Montréal, Canada
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Excitation functions of the reaction ^{10}B(^{14}N, α)^{20}Ne near the Coulomb barrier reveal clearly correlated cross-section structure in different α-particle channels. This indicates intermediate structure which had never been observed in the interaction of two nonidentical, odd-odd nuclei at such high level densities.

One of the most fascinating discoveries of heavy-ion research was the observation of sub-Coulomb-barrier resonances in the scattering of ^{12}C on ^{12}C.[1] Up until now, no quantitative understanding of the phenomenon exists, but several theoretical explanations have been introduced. The most attractive idea is based on the hypothesis that a doorway state arises from an intermediate "quasimolecular" state of two ^{12}C ions, where one of the ^{12}C nuclei is dissociated into three α particles.[2]

Many other heavy-ion reactions have been investigated[3] in order to search for resonancelike structure. At high compound-nucleus excitations, two isolated cases of single resonances have been reported, one[4] in ^{12}C + ^{16}O and one[5] in ^{12}C + ^{12}C. In the vicinity of the barrier, however, only three other examples of such resonant structure have been found so far, besides ^{12}C + ^{12}C, namely ^{12}C + ^{16}O,[6] and more weakly, ^{12}C + ^{14}C[7] and ^{12}C + ^{13}C.[8] Since resonances have been observed in only these few cases, Stokstad *et al.*[9] recently formulated the hypothesis that there might exist a correlation between the absence of such structure and a high level density in the compound nucleus. Moreover, the presence of at least one "α-particle nucleus" in the entrance channel seems to be necessary for the observation of resonances.

We would like to report in this Letter on the observation of correlated resonancelike structure close to the Coulomb barrier in the reaction ^{10}B(^{14}N, α)^{20}Ne. Here, one is populating the compound nucleus at very high level densities around 40 MeV, and neither the target nor the projectile is an "α nucleus." This reaction had already been investigated[3] in the sub-Coulomb region with no evidence for correlated resonances. With our Model EN tandem Van de Graaff accelerator, we have measured excitation functions for the (^{14}N, α) reaction on ^{10}B at three scattering angles, 0°, 30°, and 110°, and complete angular distributions for 25 and 35 MeV.[10] Measurements have been performed in steps of 104 and 208 keV (c.m.) at 0° and at 30° and 110° (lab) scattering angle, respectively, between 5.4- and 14.6-MeV (c.m.) bombarding energy, corresponding to excitation energies in ^{24}Mg between 34.3 and 43.4 MeV. Thin self-supporting targets and targets of 10–20 μg/cm^2 ^{10}B on very thin carbon backings were used. A gold layer of about 3 μg/cm^2 thickness was evaporated on these targets in order to extract absolute cross sections by normalizing on the Rutherford cross section of Au. The beam was stopped in a thin tantalum foil in front of the 0° detector. Nickel absorber foils were used at 30° to stop the elastically scattered ^{14}N particles. The small effect of kinematic broadening at 0° permits a large detector solid angle of 19 msr. At 30° and 110°, measurements have been performed with position-sensitive detectors by using large solid angles (3–10 msr) and correcting for the kinematical broadening with the help of the position signal and an on-line computer. The large detector solid angles allowed rapid measurements of small cross sections with an energy resolution as high as 60 keV. Additional high-resolution α spectra were obtained with the McMaster University's FN tandem Van de Graaff accelerator, using photoemulsions in the focal plane of the Enge split-pole magnetic spectrograph.[10] Because of the large positive Q value of 19.53 MeV, we obtained very clear α spectra up to 10-MeV excitation in ^{20}Ne.

The choice of the scattering angles was determined by the following considerations: (1) Since large statistical fluctuations have been found in the ^{12}C + ^{12}C reaction,[11] where one is populating the same compound nucleus, ^{24}Mg, as in the present experiment, we intended to look for the same fluctuating structure in our excitation functions, which were predicted by the statistical model to be strongest at 0° and 180°. (2) One also expects to be more sensitive to possible direct-transfer contributions near 0°. (3) The scattering angles 0°, 30°, and 110° were chosen wide-

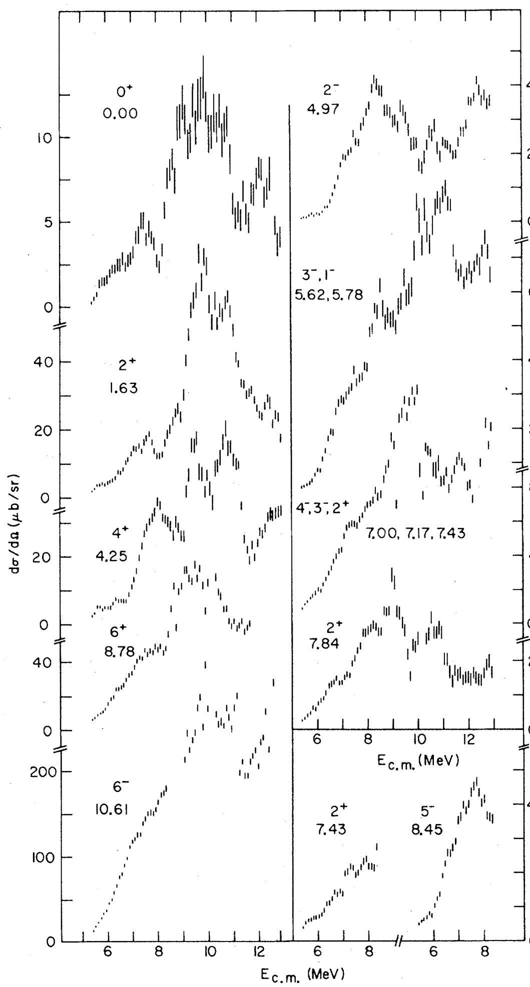

FIG. 1. Excitation functions for the reaction ${}^{10}B({}^{14}N, \alpha){}^{20}Ne$ at $\theta_{lab} = 0°$ scattering angle.

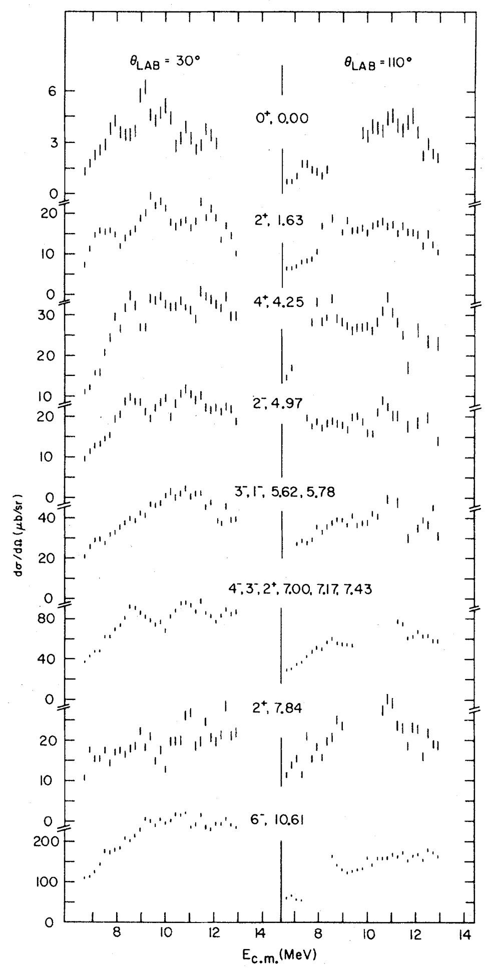

FIG. 2. The same as Fig. 1 for $\theta_{lab} = 30°$ and 110°.

ly separated to have statistically independent fluctuations (the average coherence angle for our reaction is $1/kR \sim 5°$).

Figures 1 and 2 show the measured excitation functions for several states in ${}^{20}Ne$ at 0°, 30°, and 110°, respectively. The error bars indicate the statistical uncertainties. By use of the average counting rate of two monitor detectors symmetrically positioned with respect to the beam direction, the influence of small beam movements was eliminated. The data were partly reproduced by independent measurements. By normalizing on the Rutherford scattering from gold and boron, relative cross sections are measured to better than 5%, whereas, absolute cross sections are accurate within about 10%.

In general, the average cross-section behavior is reproduced by Hauser-Feshbach statistical-model calculations, although, as previously reported,[10] slight deviations have been noticed in the angular distributions, with cross sections consistently too large at angles smaller than 50° (c.m.). However, the broad resonancelike structure observed in the excitation functions around 10 MeV at 0° and weakly at other angles is of different nature and cannot be described in terms of statistical fluctuations. The following observations were made: (1) There are sizable correlations between most α transitions; (2) the amplitude of the structure is too large for the 2^+ and 4^+ states and for the sum over many states compared with that of the 0^+ state of the ground-state band; and finally, (3) its width of about 1 MeV (c.m.) is much larger than the average fluctuation width, known from many other experiments to lie between 100 and 400 keV for our excitation region.[11]

The strength of the observed correlation is in-

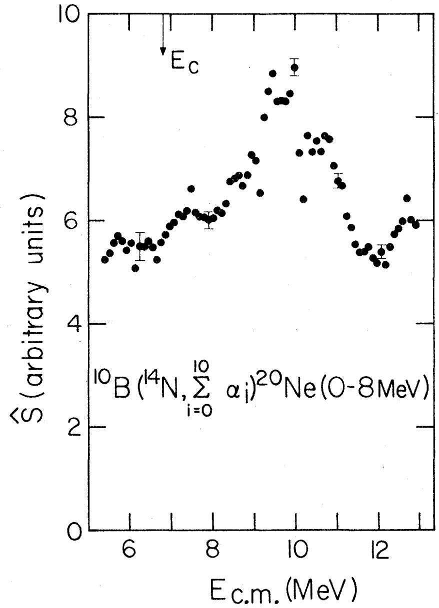

FIG. 3. Excitation function $\hat{S}(E)$, as explained in the text, representing the sum over the cross sections of the first eleven α transitions at 0°.

dicated in Fig. 3 which displays the function $\hat{S}(E) = \sigma(E)E/\sum_l(2l+1)T_l$ for the first eleven α transitions at 0°. This function is similar to the $\tilde{S}$ function defined in Ref. 6 and exhibits the summed cross section without its strong energy dependence at the Coulomb barrier. All contributing transmission functions T_l have been calculated from the optical model. As can be seen, the broad structure at 10 MeV is still very pronounced, in spite of the fact that many magnetic substates are contributing incoherently to the transitions which should accordingly lead to a strong damping of fluctuations. Taking into account the finite solid angle of $\pm 4.5°$ of our detector, we find, for the reaction $^{10}B(^{14}N, \alpha)^{20}Ne$ at 0°, the values 2.7, 19.2, and 27.0 for the effective number N_{eff} of magnetic substates contributing to the 0^+, 2^+, and 4^+ states of ^{20}Ne, respectively. At angles larger than 10°, one rapidly reaches the maximum values of 11, 53, and 95. Summing over the first eleven states of comparable cross sections and spins between 0 and 4, one obtains a value of $N_{eff}^{tot}(0°) = 197$. This implies that the mean square deviation of the cross section at 0° should not be larger than 0.5%. The analysis of the data of Fig. 3, however, leads to a value 5 times larger.

One also notices from Fig. 1 that the amplitudes of the fluctuations for the 2^+ and 4^+ states are larger than those for the 0^+ ground state, whereas, they should be damped in going from a 0^+ to a 4^+ state by the ratio of the corresponding values of $N_{eff}^{1/2}$, e.g., by a factor of 3. Strictly this is true for average fluctuations, whereas, we are dealing with a limited energy range, but it is still a further indication for the nonstatistical character of the structure.

Finally, we fitted a histogram of 36 cross-correlation values, $R_{\alpha\beta} = \langle \sigma_\alpha \cdot \sigma_\beta \rangle / (\langle \sigma_\alpha \rangle \cdot \langle \sigma_\beta \rangle) - 1$, with a Gaussian about zero. We then found that 15% of the surface lies outside of the Gaussian, again indicating sizable correlations.[10]

From all this, we conclude that the gross structure observed in the reaction $^{10}B(^{14}N, \alpha)^{20}Ne$ at low bombarding energies is not due to statistical fluctuations, but rather indicates the presence of intermediate structure in ^{24}Mg. The fact that statistical fluctuations are weak, if present at all, even for low-spin transitions at 0°, is in obvious contrast to the reaction $^{12}C(^{12}C, \alpha)^{20}Ne$,[11] which also populates the ^{24}Mg compound nucleus. On the other hand, the two reactions are not at all similar. Besides the large structural differences between the nuclei involved, both systems have very different dynamical properties: (1) Whereas for $^{12}C + ^{12}C$ one has two identical bosons and channel spin 0, one has two very different nuclei with a maximum channel spin of 4 for $^{10}B + ^{14}N$. Therefore, for the latter system, there are no restrictions concerning the population of odd, negative-parity states *and* unnatural-parity states, resulting in many more contributing partial cross sections. (2) At 35.8-MeV excitation in ^{24}Mg, corresponding to the Coulomb barrier of $^{10}B + ^{14}N$, one has very different angular momenta for the two systems, with $kR = 18$ and 10 for $^{12}C + ^{12}C$ and $^{10}B + ^{14}N$, respectively. (3) Finally, the angular momenta in the entrance and exit channels are nearly matched for our reaction, which is not true for $^{12}C(^{12}C, \alpha)^{20}Ne$.

The occurrence of intermediate structure, most pronounced for the low-spin transitions, could be due to a low-spin doorway state in ^{24}Mg, having fairly large overlap with the rather pure $(sd)^4p^0$ configuration of the ^{20}Ne ground-state band. Since the cross section for an isolated resonance with definite spin is largest at 0 and π, we expect maximum cross-section enhancements at these angles. The observed structure is, however, quite complicated and shows up differently in the various channels, thus diminishing the resonant effect in the summed cross section and the strength of the cross correlations. This feature can readily be explained either by the configuration of the doorway state leading to different intermediate structures in different channels or by the occurrence of interference between overlapping doorway states and possibly direct reaction contributions.[12] These two effects might upset correlation studies and cast some doubt on the common procedures for identifying intermediate structure by total cross-section measurements and cross correlations.

In conclusion, we emphasize that the nonstatistical cross-section behavior observed in the interaction of two "non-α-particle" nuclei at very high level densities suggests the existence of rather simple doorway-state configurations in the nuclear continuum with a small spreading width.

[1]E. Almqvist, D. A. Bromley, and J. A. Kuehner, Phys. Rev. Lett. 4, 365, 515 (1960).

[2]G. Michaud and E. W. Vogt, Phys. Lett. 30B, 85 (1969), and Phys. Rev. C 5, 350 (1973).

[3]H. Voit *et al.*, Nucl. Phys. A179, 23 (1972).

[4]R. E. Malmin *et al.*, Phys. Rev. Lett. 28, 1590 (1972); R. Stokstad *et al.*, Phys. Rev. Lett. 28, 1523 (1972); E. R. Cosman *et al.*, Phys. Rev. Lett. 29, 1341 (1972).

[5]K. Van Bibber *et al.*, Phys. Rev. Lett. 32, 687 (1974).

[6]J. R. Patterson *et al.*, Nucl. Phys. A165, 545 (1971), and Nature (London), Phys. Sci. 231, No. 18, 17 (1971); H. Voit *et al.*, Z. Phys. 255, 425 (1972); M. L. Halbert *et al.*, Nucl. Phys. 67, 277 (1965).

[7]M. Feil *et al.*, Z. Phys. 260, 271 (1973).

[8]D. J. Crozier and J. C. Legg, Phys. Rev. Lett. 33, 782 (1974).

[9]G. Stokstad, in *Lecture Notes in Physics*, edited by J. Ehlers, K. Hepp, and H. A. Weidenmüller (Springer, Berlin, 1973), Vol. 22, p. 179, and in *Proceedings of a Symposium on Heavy Ion Transfer Reactions*, Argonne National Laboratory Report No. CONF 730312-1, 1973 (National Technical Information Service, Springfield, Va., 1973), Vol. 1, p. 325; D. L. Hanson *et al.*, Phys. Rev. C 9, 1760 (1974).

[10]N. Marquardt, R. Volders, C. Cardinal, and J. L'Ecuyer, in *Proceedings of a Symposium on Heavy Ion Transfer Reactions*, Argonne National Laboratory Report No. CONF 730312-2, 1973 (National Technical Information Service, Springfield, Va., 1973), Vol. 2, p. 613, and in *Proceedings of the International Conference on Nuclear Physics, Munich, Germany, 1973*, edited by J. de Boer and H. J. Mang (North-Holland, Amsterdam, 1973), Vol. 1, p. 476, and in *Proceedings of the International Conference on Reactions between Complex Nuclei, Nashville, Tennessee, 1974*, edited by R. L. Robinson, F. K. McGowan, J. B. Ball, and J. H. Hamilton (North-Holland, Amsterdam, 1974), Vol. 1, p. 93.

[11]L. R. Greenwood, R. E. Segel, and J. R. Erskine, in *Proceedings of the International Conference on Nuclear Physics, Munich, Germany, 1973*, edited by J. de Boer and H. J. Mang (North-Holland, Amsterdam, 1973), Vol. 1, p. 543; D. Shapira, R. G. Stokstad, and D. A. Bromley, to be published, and literature therein.

[12]H. Feshbach, A. K. Kerman, and R. H. Lemmer, Ann. Phys. (New York) 41, 230 (1967); H. Feshbach, in *Proceedings of the International Conference on Nuclear Physics, Munich, Germany, 1973*, edited by J. de Boer and H. J. Mang (North-Holland, Amsterdam, 1973), Vol. 2, p. 631.

Isospin-Conservation Violation in Two-Nucleon Transfer Reactions

George L. Strobel
The University of Georgia, Athens, Georgia 30602
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The analog $(p,{}^3\mathrm{He})$ and (p,t) reactions on ^{16}O have been studied by a second-order distorted-wave Born-approximation (DWBA) theory. Nucleon transfer is assumed to occur here only one nucleon at a time. The contribution of the isospin-1 intermediate-state projectile was made small at forward angles by increasing the imaginary part of the corresponding optical potential. This increase can be associated with the preferential decay of an isospin-1 projectile. Convergence of the DWBA is studied by comparing one- and two-step calculations.

Isospin conservation predicts the differential cross sections for $(p,{}^3\mathrm{He})$ and (p,t) reactions to have the ratio $k_{^3\mathrm{He}}/2k_t$ for protons on an isospin-zero target. Ingalls[1] has studied this prediction for 27-MeV protons on an oxygen target. He has measured the $^{16}\mathrm{O}(p,{}^3\mathrm{He})^{14}\mathrm{N}^*(2.31\ \mathrm{MeV},\ T=1)$ and the $^{16}\mathrm{O}(p,t)^{14}\mathrm{O}(0.00\ \mathrm{MeV},\ T=1)$ reaction cross sections for scattering angles less than 40°. For small scattering angles, less than 22.5°, the isospin-conservation prediction is satisfied,