TABLE II. ^{238}U average fission cross section.

Energy range (keV)	Average fission cross section This experiment (μb)	Ref. 1 (μb)
10–30	87 ± 26	61 ± 24
30–100	40 ± 12	36 ± 14

columns 5 and 6 results primarily from the uncertainty in the ^{235}U content of the ^{238}U fission chambers.

These results can be compared to the keV energy measurements of Silbert and Bergen[1] by summing the ^{238}U fission counts over the two neutron energy intervals $10 \leq E_n \leq 30$ keV and $30 \leq E_n \leq 100$ keV. Using Eq. (3) and the average σ_f values taken from data in Ref. 3 over these energy intervals, the average fission cross section for ^{238}U is obtained. These results are presented in Table II along with the results of Silbert and Bergen; within the experimental errors both measurements are in good agreement in this energy range. It is thus interesting that we agree with Silbert and Bergen in the average ^{238}U fission cross section, but that they did not report the observation of these fission clusters near 720 and 1210 eV.

In conclusion, this is the first observation (to our knowledge) of well-resolved and well-defined neutron-induced subthreshold fission in ^{238}U, and thus is a confirmation of the existence of a double-humped barrier in ^{239}U.

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(^{10}B, ^{7}Li) and (^{10}B, ^{7}Be) Analog Reactions on ^{12}C†

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The reactions ^{12}C(^{10}B, ^{7}Li)^{15}O and ^{12}C(^{10}B, ^{7}Be)^{15}N were investigated at 100 MeV incident energy. These analog reactions show almost identical features, as expected, because the incident energy is much higher than the Coulomb barriers. Therefore, these reactions represent a powerful reaction-mechanism–independent method of finding corresponding analog states in the residual nuclei. Furthermore, the data are consistent with the assumption that the processes are direct three-nucleon transfers populating high-spin states. We identify the states having two-particle, three-hole and three-particle, four-hole configurations coupled to high spins.

Despite the potential interest in and importance of heavy-ion–induced reactions, inherent difficulties involved in understanding their reaction mechanisms often hinder the extraction of quantitative structure information. In this Letter, it is demonstrated that analog states in mirror nuclei may be identified from the experimental results regardless of the reaction mechanism. It is also proposed that certain types of heavy-ion reactions are very powerful tools for obtaining structure information. The reactions ^{12}C(^{10}B, ^{7}Li)^{15}O and ^{12}C(^{10}B, ^{7}Be)^{15}N were studied to obtain such information. Several states in mass-15 systems were identified and their analog correspondence established. There are also indications that these reactions are direct three-nucleon transfer processes which allow extraction of structure information for the states.

Reactions in which incident self-conjugate nuclei produce analog final channels should be identical except for Coulomb effects. By choosing the incident energy to be much higher than the Coulomb barrier, Coulomb distortions and Q-value differences (reflecting the Coulomb effects in the structure) should produce negligibly small differences in the outgoing channels. In the present case, the Coulomb barriers in the incident and outgoing channels are about 8 MeV, and the ground-state Q values are -5.715 and -3.817 MeV for the reactions $^{12}C(^{10}B, ^{7}Li)^{15}O$ and $^{12}C(^{10}B, ^{7}Be)^{15}N$, respectively. In fact, use of analog reactions to find corresponding information in mirror nuclei has been used in various cases. Especially, the reactions (^{6}Li, t) and (^{6}Li, ^{3}He) were successfully utilized for spectroscopic studies of the ^{19}F and ^{19}Ne [1] and the ^{17}O and ^{17}F [2] nuclei. It should be noticed that an extension of such applications to the use of high-energy heavy-ion reactions should provide additional interest. The reaction dynamics usually enhances high-excitation and high-spin states. Consequently, such a measurement can selectively find a certain class of states. Furthermore, the idea can be extended to not only measurements of mirror nuclei but also measurements of all isobaric multiplet states if proper reaction channels are observed.

A beam of 100-MeV ^{10}B ions from the Texas A & M University cyclotron was used to bombard a 240-g/cm^2 natural-carbon target. The beam intensity was typically 300 nA with $^{10}B^{5+}$. A three-detector counter telescope[3] was used with 50, 50, and 1000-μm solid-state detectors for ΔE_1, ΔE_2, and E counters, respectively. Double particle identification with Ortec particle identifiers provided complete isotone separation up through the carbon isotopes. The energy resolution obtained was almost completely governed by kinematic broadening due to the finite angular resolution (0.2°), and was typically 300 keV. Energy calibrations were obtained from the known states in various outgoing channels, and were checked for consistency among different isotopes. The uncertainty of the excitation energies quoted is conservatively estimated to be 150 keV. The zero angle was determined within 0.2° by a 0° measurement of residual beam with the ion source off.

In Fig. 1, typical spectra from these two reactions are shown and, as expected, are very similar. Moreover, the absolute cross sections for, and angular distributions of, analog peaks (Fig. 2) are identical (within the errors), while different sets of states have different distributions. This confidently pinpoints analog states. The analog pairs identified in this experiment are in ^{15}O and ^{15}N, respectively, 9.64 and 9.87 MeV, 10.47 and 10.78 MeV, 12.89 and 13.15 MeV, 15.36 and 15.72 MeV, 15.88 and 16.26 MeV, and 17.13 and 17.83 MeV. The 15.88-16.26-MeV pair does

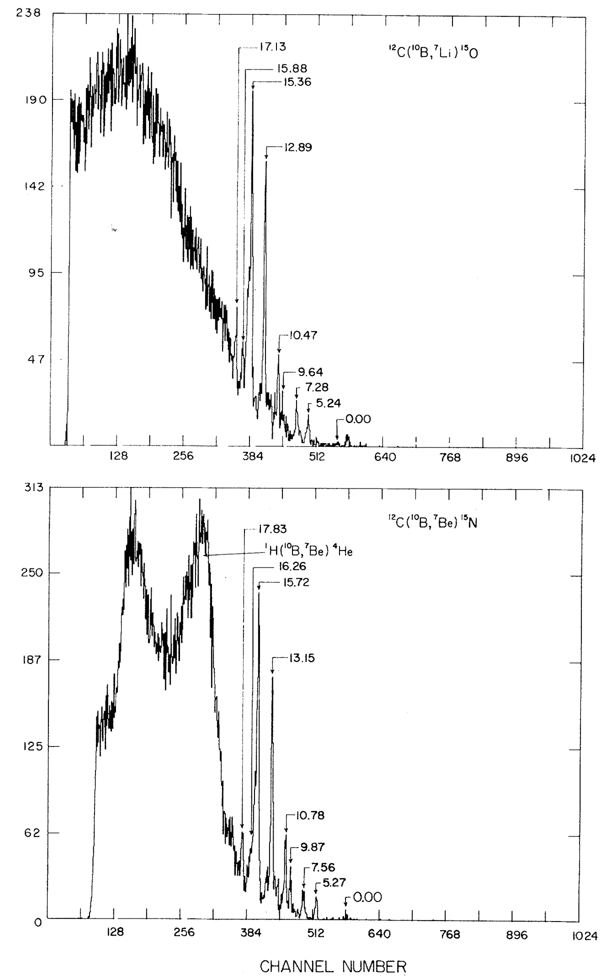

FIG. 1. Energy spectra from the reactions $^{12}C(^{10}B, ^{7}Li)^{15}O$ and $^{12}C(^{10}B, ^{7}Be)^{15}N$ taken simultaneously at $\theta_{lab} = 14°$. Excitation energies obtained are indicated for each peak. The uncertainty in the energy calibration was estimated to be 150 keV. The peak above the ground state in the ^{7}Li spectrum is not completely understood. It could, however, be a detection of ^{8}Be in such a fashion that two α particles were detected simultaneously, since the particle identification could not separate such events from ^{7}Li (in fact, the peak position agrees with the transition to the 8.96-MeV 5^+ state in ^{14}N).

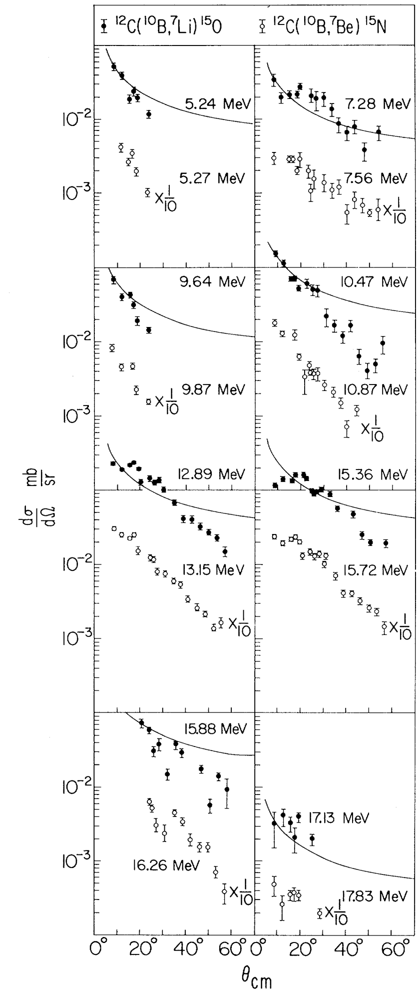

FIG. 2. Angular distributions for analog pairs, indicated by their excitation energies. The error bars are statistical only, and the absolute cross sections were determined with estimated uncertainties of 25%. The curves drawn indicate the $1/\sin\theta$ shape.

not show up well in Fig. 1, but was unambiguously established from the other spectra obtained.

Besides the identification of the analog pairs, several interesting points should be noted. Scott *et al.*[3] studied a variety of reactions using high-energy (~10 MeV/nucleon) heavy-ion beams. A spectrum from the reaction $^{12}C(^{12}C, ^{9}Be)^{15}O$ obtained at $\theta_{lab} = 15°$ in Ref. 3 is very similar to that from $^{12}C(^{10}B, ^{7}Li)^{15}O$ (Fig. 1). The states at 5.24, 7.28, 12.83, and 15.08 MeV in ^{15}O were populated with similar relative strengths in both reactions. [The energies obtained for the strong state at ~15 MeV by Ref. 3 (15.08 MeV) and by us (15.36 MeV) differ slightly.[4]] Similarly, a spectrum at $\theta_{lab} = 7°$ from the reaction $^{12}C(^{11}B, ^{8}Li)^{15}O$ shows the same selective populations of the 7.28-, 12.83-, and 15.08-MeV states.[5] On the other hand, the reaction $^{13}C(^{11}B, ^{9}Li)^{15}O$ at $\theta_{lab} = 6°$ shows no population of the 15.08-MeV state.[15] The reaction[5] $^{13}C(^{11}B, ^{9}Be)^{15}N$ at $\theta_{lab} = 6°$ also shows different features from $^{12}C(^{10}B, ^{7}Be)^{15}N$, and the 15.72-MeV state observed in the present experiment is not strongly populated. The results are, however, similar to those obtained by Lu, Zisman, and Harvey,[6] who studied the reaction $^{13}C(\alpha, d)^{15}N$. In the former reaction populations of the states at 5.27, 7.56, 9.72, 11.79, and 12.87 MeV were observed, while in the latter, they identified states at 5.27, 7.58, 9.81, 11.95, and 13.03 MeV in addition to the fairly strong ground state.

The results indicate a strong selectivity in these reactions in addition to the usual transferred angular momentum and Q-value dependences.[7] This selectivity implies that the reaction is primarily direct rather than compound. In addition, our angular distributions do not peak in the region of observation, in agreement with a simple estimate of the grazing angle[7] ($\lesssim 7°$) for these reactions. It is also seen (Fig. 2) that the data do not follow a $1/\sin\theta$ dependence, although the asymptotic behavior of an angular distribution of the compound process with many partial waves should follow such a curve.[8] The data for the reaction $^{12}C(^{10}B, ^{6}Li)^{16}O$ taken simultaneously[9] showed only very weak excitation of discrete states, although one might naively expect strong direct α-particle transfer. However, it has been argued[10] that a strong component of [3, 1] symmetry in the ^{10}B ground-state wave function tends to wash out any strong selectivity. On the other hand, such structure is favorable for three-nucleon stripping reactions with ^{10}B projectiles. The semiclassical treatment of Brink,[11] successfully applied to several cases,[3,12] predicts a certain selectivity for such transfer processes. We found that the rule works quite well if we assume spins and parities for the states as described below. Especially, these reactions preferentially populate the states with stretch coupling for a given configuration, since population of high-spin states is favored.

The experimental features described above can be consistently understood with these considerations. In two-nucleon transfer reactions on ^{13}C, one would expect to populate excited states with particles in the sd shell and holes in p shell. The 7.28-MeV state in ^{15}O, identified as having the $[(d_{5/2})(p_{1/2})^2]_{7/2^+}$ configuration,[13] is indeed strongly populated by two-nucleon transfer. Lu, Zisman, and Harvey[6] concluded that the states at 11.95 and 13.03 MeV in ^{15}N, populated by the two-nucleon transfer, have $[(d_{5/2})^2 p_{1/2}]_{9/2^-}$ and $[(d_{5/2})^2 \times p_{1/2}]_{11/2^-}$ configurations, respectively. These states were also observed in the reaction ^{13}C(^{11}B, ^{9}Be)^{15}N by Anyas-Weiss *et al.*[5] The states we observed at 13.15 MeV in ^{15}N and 12.89 MeV in ^{15}O thus should be identified as the $[(d_{5/2})^2 p_{1/2}]_{11/2^-}$-configuration states. However, in the present reactions, the $\frac{9}{2}^-$ states were not observed strongly. A peak was observed in the present reaction and in the reactions ^{12}C(^{12}C, ^{9}Be)^{15}O at about 12.0 MeV,[4] but was very much weaker than the 12.89-MeV state. The reaction mechanism must play a vital role in this difference between populations of the $\frac{11}{2}^-$ and $\frac{9}{2}^-$ states in the two- and three-nucleon transfer reactions.

In the three-nucleon transfer reactions, one would expect strong transitions to states of the configuration $[(d_{5/2})^3(p_{1/2})^{-4}]$. Scott *et al.*[3] associated a state in ^{15}O at 15.08 MeV, which is presently identified at 15.36 MeV, with this configuration coupled to $\frac{13}{2}^+$. The state at 15.72 MeV in ^{15}N must be the analog of this ^{15}O state. This spin assignment is consistent with Brink's semiclassical selection rules, and these are the strongest peaks in the spectra. The observation of the pair at 9.64 and 9.87 MeV and the high-spin preference in the present reactions may provide support to the assignment of Lambert and Durand.[14] They suggested the analog correspondence of the states at 9.67 MeV ($\frac{7}{2}^-$, $\frac{9}{2}^-$) and 9.83 MeV ($\frac{7}{2}$), in ^{15}O and ^{15}N, respectively, while Honsaker *et al.*[15] suggested the 9.66-MeV state in ^{15}O to be $(\frac{1}{2})^-$. States at 10.47 and 10.78 MeV, and 17.13 and 17.83 MeV, in ^{15}O and ^{15}N, respectively, were also populated fairly strongly in the present reaction, and in the reaction ^{12}C(^{12}C, ^{9}Be)^{15}O.[5]

There is no *a priori* reason for the detected ^{7}Li and ^{7}Be to be in their ground states, however, the energies obtained for the known states at 5.27 and 7.56 MeV in ^{15}N and their analogs in ^{15}O are consistent with no excitation of the outgoing projectiles (the energies obtained were consistent within 35 keV). The 15.72- and 15.36-MeV groups in the ^{7}Li + ^{15}N and ^{7}Be + ^{15}O channels, respectively, (see Fig. 1) were the only possible doublets with approximately correct spacing for excitation of the first excited ^{7}Li and ^{7}Be states.

In conclusion, we propose that analog reactions be utilized to identify corresponding analog states. As one does not have to worry about reaction mechanisms, this is a potentially powerful use for heavy-ion reactions as demonstrated by the present example. Furthermore, if the reactions are direct-transfer processes, the technique provides a new method which may be used to locate high-spin analog states in regions of high excitation.

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