We can now draw some tentative conclusions about (p, 2p) and (p,pn) reactions in this energy range. (1) For our detector arrangement, (p, 2p) reactions are isotropic whereas (p,pn) reactions apparently are not. In addition to our data and Ref. 13 for ^{2}H, the reaction[16] ^{3}H(p, 2p)nn at 46 MeV is consistent with this pattern. (2) Target-dependent effects are evident in the angular behavior of the (p,pn) reaction: The angular behaviors of the reactions ^{6}Li(p,pn) and ^{2}H(p,pn) are very similar, and both are different from ^{13}C and ^{9}Be. (3) Nucleon knockout experiments with nonidentical particles at unequal angles reveal complexities in the reaction mechanism which are masked in symmetric (p, 2p) experiments.

A more sophisticated distorted-wave analysis of our data is in progress, and may be able to explain the behavior of the (p,pn) reaction at this energy. We plan to extend our study of (p,pn) reactions to other light nuclei; it will be interesting to see if the observed systematics persist.

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Resonance in the Reaction ^{12}C(^{12}C,p)^{23}Na at $E_{\text{c.m.}}$ = 19.3 MeV*

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Excitation functions of the fifteen most strongly populated states ($9 < E_x < 17$ MeV) in the reaction ^{12}C(^{12}C,p)^{23}Na have been studied using a magnetic spectrograph. A resonance structure was observed for transitions to several final states at $E_{\text{c.m.}} = 19.3$ MeV with $\Gamma_{\text{c.m.}} \cong 500$ keV. Two particle-bound states in ^{23}Na at 9.08 and 9.84 MeV are particularly strongly populated in the reaction ^{12}C(^{12}C,p) at the resonant energy. The further study of the structure of these states may provide an important clue to the nature of the observed ^{12}C + ^{12}C resonance.

Intermediate structure was observed in the ^{12}C + ^{12}C system near and below the Coulomb barrier by the experiments of Almqvist, Bromley, and Kuehner[1] in 1960; they located correlated resonances in the total yield of p, n, α, and γ radiations from the ^{12}C + ^{12}C reaction. Somewhat less pronounced sub-Coulomb-barrier resonances have also been observed[2] in $^{12}C+^{16}O$ and to date these are the only two heavy-ion systems for which such low-energy structure has been clearly identified.[3]

In the last three years extensive studies of $^{12}C+^{12}C$ and $^{12}C+^{16}O$ well above the barrier have been made in search of further intermediate structure. A single resonance at $E_{c.m.}=19.7$ MeV in the $^{12}C+^{16}O$ system has been documented by several groups[4] and observed in the excitation functions of the elastic, inelastic, p, and (possibly) α exit channels. Until now all searches on $^{12}C+^{12}C$ well above the Coulomb barrier have yielded negative or ambiguous results.[5] Here we report a pronounced resonant structure at $E_{c.m.}=19.3$ MeV in the reaction $^{12}C+^{12}C\rightarrow p+^{23}Na^{*}$ to selected, highly excited states of ^{23}Na.

We studied the reaction[6] $^{12}C(^{12}C,p)^{23}Na$ using the Brookhaven National Laboratory double MP tandem Van de Graaff accelerator facility. The proton energy spectra (overall resolution ~ 50 keV) were detected at $\theta_{lab}=7.5$ and 15° with the Massachusetts Institute of Technology multiple-gap spectrograph. The exits from all gaps but those at $\theta_{lab}=7.5$ and 15° were covered by Pb foils thick enough to stop all emerging particles; the instrument's unique 360° nuclear-emulsion holder carousel was sequentially rotated over the two open gaps, thus allowing 36 proton spectra to be collected at each angle at different beam energies without breaking the vacuum. Spectra were observed at seven energies between $E_{c.m.}=10$ and 15 MeV while detailed excitation functions were measured between $E_{c.m.}=16$ and 22 MeV in steps as small as 50 keV. The nominal target thickness was 15 $\mu g/cm^2$, typical exposure lengths were 1500 μC, and frequent repeat runs were made to detect possible carbon buildup on the target. Excitation energies of ^{23}Na groups are accurate to ± 50 keV, and the overall cross-section scales quoted below are estimated to be accurate to better than 40%. In addition, full proton angular distributions were measured in the conventional multiple-gap mode on and off the $E_{c.m.}=19.3$ MeV resonance energy.

The excitation functions for the most prominent transitions seen between $E_x=9$ and 17 MeV are shown in Fig. 1 for the $\theta_{lab}=7.5°$ data. The most striking effect is the anomaly at $E_{c.m.}=19.3$ MeV. It is especially pronounced for the $E_x=9.07$- and 9.84-MeV transitions and visible to a lesser degree in transitions to the $E_x=12.55$-, 14.43-, 14.56-, (15.98+16.01)-, 16.32-, and 16.60-MeV levels. Proton yields excluding these states showed no significant anomaly at $E_{c.m.}=19.3$ MeV. The half-width of the anomaly is $\Gamma_{c.m.}$ ~ 500 to 600 keV. The angular distributions measured on the resonance for the E_x ~ 9-MeV doublet were strongly peaked at forward angles whereas off resonance they are flat and low, implying that the resonance structure persists at the for-

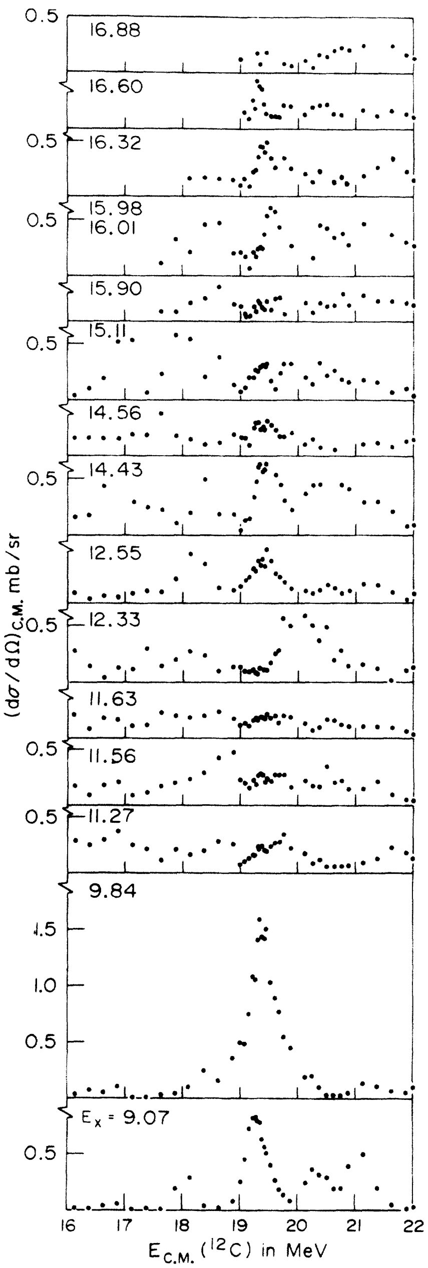

FIG. 1. Excitation functions of fifteen most prominent proton transitions. $\theta_{lab}=7.5°$.

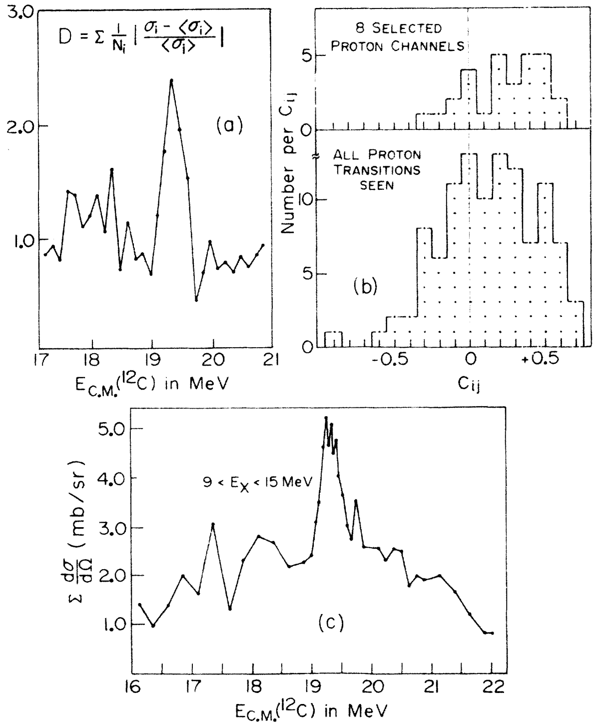

FIG. 2. (a) Summed deviations of all transitions; $\langle\sigma_i\rangle$ is the local average (determined for an averaging interval $\epsilon = 2.25$ MeV). (b) Distribution of cross-correlation coefficients defined as $C_{ij} = R_{ij}/(R_{ii}R_{jj})^{1/2}$, where $R_{ij} = \langle\sigma_i\sigma_j\rangle/\langle\sigma_i\rangle\langle\sigma_j\rangle - 1$ and the averaging interval is $\epsilon = 1.5$ MeV. For the lower distribution, a χ^2 test indicates that there is less than 1% probability that it arises from a Gaussian distribution with mean value 0, indicating its nonstatistical character. (c) Summed cross sections for nine states presumed resonating. $\theta_{\mathrm{lab}} = 7.5°$ for all cases.

ward angles. Strong selectivity in the population of ^{23}Na states was observed in general at all energies.

Some common procedures for investigating the statistical character of such a phenomenon are displayed in Fig. 2. These tests strongly suggest the conclusion that the 19.3-MeV anomaly is of nonstatistical origin and thus constitutes an intermediate structure in the ^{12}C + ^{12}C system correlated in several p + ^{23}Na exit channels. The ^{12}C + ^{12}C resonance reported here at $E_{\mathrm{c.m.}} = 19.3$ MeV, $E_x(^{24}\mathrm{Mg}) \cong 33.2$ MeV, with $\Gamma_{\mathrm{c.m.}} \sim 500$ keV, is similar in some ways to the previous ^{12}C + ^{16}O resonance: $E_{\mathrm{c.m.}} = 19.7$ MeV, $E_x(^{28}\mathrm{Si}) \cong 36.5$ MeV, with $\Gamma_{\mathrm{c.m.}} \sim 500$ keV. Both resonances display prominent proton decays; $E_x = 9.07$ and 9.84 MeV in ^{23}Na and $E_x = 15.53$ and 15.83 MeV in ^{27}Al, respectively. In contrast to the ^{12}C + ^{16}O resonance, however, the ^{12}C + ^{12}C anomaly has not been detected in other charged-particle channels. Extensive searches and analyses of the elastic, $^{12}\mathrm{C}^*(2_1^+)$, and α channels have revealed strong compound-nucleus fluctuations but to date no obvious nonstatistical structure[5] has been found. A recent study of $^{12}\mathrm{C}(^{12}\mathrm{C}, n)^{23}\mathrm{Mg}$ by Sperr *et al.*[7] over the region of the 19.3-MeV resonance has shown a dramatic enhancement to a state at $E_x = 9.6 \pm 0.1$ MeV in ^{23}Mg. Its on-resonance yield is very close to that for the $E_x = 9.84$-MeV state in ^{23}Na and thus these states are most probably mirror configurations.

In the statistical compound-nucleus model the enhanced transitions in the reaction $^{12}\mathrm{C}(^{12}\mathrm{C}, p)^{23}\mathrm{Na}$ lead to ^{23}Na states with high spins, since much more orbital angular momentum is brought in by the ^{12}C + ^{12}C entrance channel than can be carried off by the outgoing proton. The observed average energy distribution of the outgoing protons as well as the average cross section for the reaction $^{12}\mathrm{C}(^{12}\mathrm{C}, p)$ agree well with Hauser-Feshbach calculations.[8] It may thus be possible to interpret the present data within the framework of a compound nuclear mechanism.

The nature of the ^{24}Mg compound state corresponding to the 19.3-MeV resonance and of the ^{23}Na states excited preferentially in the decay of the compound level is not known presently. The 9.07- and 9.84-MeV states showing the most pronounced resonance behavior are essentially particle bound and their γ decays are consequently measurable. Such data would greatly help elucidate the nature of the observed resonance.

The 19.3-MeV resonance corresponds to an excitation energy of 33.2 MeV in ^{24}Mg, while an extrapolation of the ground-state rotational band would predict a 12^+ state near 35 MeV. One attractive speculation is to associate the 19.3-MeV resonance with the ^{24}Mg ground-state band and consequently associate the preferred ^{23}Na levels with states having a large one-proton-hole parentage in the ^{24}Mg ground state. Such an interpretation has simple consequences for the γ decays of the 9.07- and 9.84-MeV states which should lead to a band head strongly excited in proton pickup on ^{24}Mg, e.g., the ^{23}Na ground-state band. Extrapolations of the ^{23}Na low-lying band structure using a rotational model predict states of high spins $(\frac{15}{2}, \frac{17}{2})$ in the vicinity of 10 MeV. Another test of the above speculation would be the detection of another resonance, corresponding to the 10^+ member of the ^{24}Mg ground-state band, near 25 MeV excitation (or

$E_{\mathrm{c.m.}} \sim 11.3$ MeV).

The above is speculation and it must be born in mind that in cases where strong absorption is present, like $^{12}\mathrm{C}+{}^{12}\mathrm{C}$, predictions have been made of resonant behavior on a strictly statistical basis.[9] However, it is indicated that a simple interpretation with appealing consequences may be possible and that the understanding of the 19.3-MeV resonance may be learned from further experimentation.

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Classical Description of the Deuteron *D*-State Effects in Sub-Coulomb (*d*, *p*) Reactions

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The effects of the deuteron *D* state on sub-Coulomb (*d*,*p*) reactions are explained in terms of a simple physical model. The model, which is based on a classical description of the reaction, makes it possible to understand the observed *D*-state effects for $^{208}\mathrm{Pb}(d,p)^{209}\mathrm{Pb}$ at 9 MeV.

In an earlier Letter[1] it was demonstrated that the deuteron *D* state has an important effect on some of the measurable quantities for (*d*, *p*) reactions. The effects are especially large for the tensor analyzing powers (T_{20}, T_{21}, T_{22}), which are a measure of the change in cross section which results when the incident deuteron beam is aligned.[2]

In this Letter we will present a model of the (*d*, *p*) reaction which is based on the concepts of classical physics. The purpose of this model is to provide a basis for understanding, in simple terms, why the deuteron *D* state affects the tensor analyzing powers for a (*d*, *p*) reaction.

The model which we propose is applicable to sub-Coulomb reactions. For sub-Coulomb energies, the reactions occur primarily outside the nucleus where the nuclear forces between the targets and projectiles have little influence on the reaction.[3] The special properties of sub-Coulomb reactions which make it possible to use a classical picture have been discussed in the literature.[3,4] Classical models have previously been used to explain the cross section[4,5] and the vector analyzing power[4] of sub-Coulomb (*d*, *p*) reactions. Models of this type are valuable because they provide physical insight which is often obscured in more formal treatments involv-