transfer population. This buildup of the naphthalene concentration to the second stimulated emission is comparable to the buildup reported by Maiman et al.[4] for the ^2E threshold for Cr^{+++} in ruby. These authors reported a delay of 300 microseconds before stimulated emission sets in after commencement of the exciting flash. In our case the benzophenone triplet plays the role of the energy source. We note that this interpretation provides a method for assessing the rate of energy transfer, and this appears to proceed at a rate comparable with the rate of triplet → singlet radiative process. Further comment on this point must await further work which is proceeding.

In the experiments recorded in Fig. 2(c) the sample appears to have persisted in a state of continuous "oscillation" after the main burst, although the concentration of naphthalene is apparently below the threshold value. In this case the energy is utilized in maintaining the light oscillations and is therefore unable to build up the triplet naphthalene concentration.

We wish to thank Dr. A. I. Vogel for the provision of facilities for this work.

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MUTUAL EXCITATION VIA A TWO-PHONON SURFACE INTERACTION IN $C^{12}(C^{12}, C^{12*})C^{12*}$†

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(Received December 8, 1961)

Recently there has been considerable interest in explaining certain nuclear inelastic scattering processes by expanding the interaction potential to second order in the surface deformation parameter.[1-3] The phenomena explained by such a treatment involve excited levels termed 2-phonon surface states. In a scattering event where the projectile as well as the target has bound excited states, a 2-phonon reaction of a somewhat different nature may occur. When two potentially deformable nuclear surfaces are involved in a reaction, expansion of the potential to second order gives rise to a 2-phonon term that can cause a single phonon of excitation in each nucleus. Using reasonable parameters, this process yields a cross section of the order of 5 millibarns at 32° c.m. This Letter reports a measurement of the angular distribution of such a process and its agreement with a calculation assuming a 2-phonon process.

As the energy levels in C^{12} are well separated, and as data have been recently accumulated[4,5] for $C^{12}(C^{12}, C^{12\prime})$ at 125-Mev lab energy, this system was the one studied. It should be pointed out that scattering to the first excited state of C^{12} (Q = -4.43 Mev) was the predominant inelastic event by a factor of at least 5, and that the angular distribution of this process was fitted well with either a Born[6] or adiabatic[7] approximation, which assumes a direct surface interaction through the deformed part of the nuclear potential. The preferential excitation of the first excited state indicates that if each nucleus is to become excited via a surface interaction the event will most likely take place with a Q of -8.86 Mev.

The energy spectrum (Fig. 1) shows groups corresponding to reaction Q values of $Q = 0.00$, -4.43, -9.00 ± 0.50, and -15 ± 1 Mev. Contributions to the $Q = -9$ Mev group could come from two sources; excitation of one nucleus to the 9.63-Mev level and, or, the excitation of both nuclei to their first excited state. Energy resolution alone is not sufficient to separate the possibilities due to a 1% spread in the incident beam energy. The separation can be effected, however, by making use of the α-particle instability of the 9.63-Mev level. Two solid-state detectors, operated in coincidence, were set at a forward scattering angle and a kinematically determined recoil angle appropriate for a given reaction. The contributions of the 9.63-Mev level to the coincidence counting rate have been estimated and are small, e.g., less than 2% of its noncoincident cross section at 18° scattering angle. Calculations of this

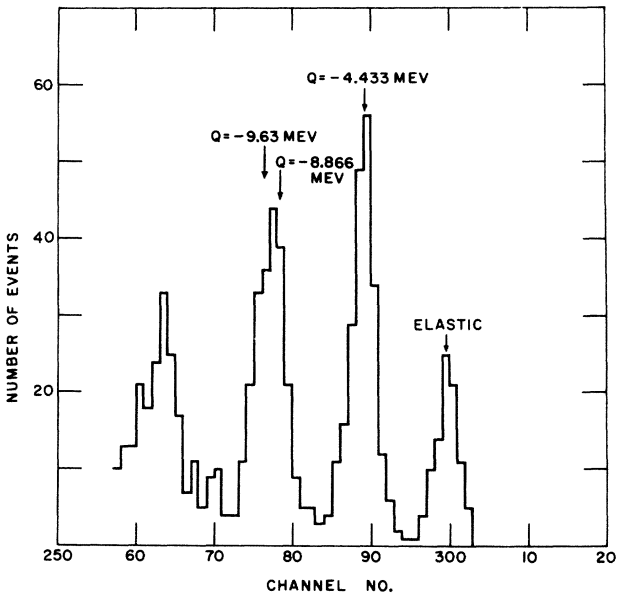

FIG. 1. Energy spectrum of particles detected at an angle of $19\frac{1}{2}°$ in the laboratory system with a beam energy of 125 Mev.

contribution considered the recoiling excited C^{12} nucleus to have no spin projection along the recoil direction consistent with the assumption of plane waves and a direct surface interaction.

The resulting experimental angular distribution of the mutual excitation process is presented in Fig. 2. Relative and absolute cross sections are accurate to 10% and 15%, respectively. First it is to be noted that the distribution of the mutual excitation (curve B) is clearly out of phase with the distribution of the single nucleus excitation (curve A). Secondly the extrema of B do not change as rapidly in magnitude with scattering angle as do the extrema of A. The results of a calculation presented below can account for both facts.

Initially, calculation of inelastic angular distributions that proceed via a direct surface interaction considered the interaction to only first order in the deformation parameter. In order to account for some anomalous behavior in $Fe^{56}(\alpha, \alpha')$ and $Ni^{60}(\alpha, \alpha')$, Lemmer et al. showed the importance of retaining second order terms. When both target and projectile are amenable to surface excitation the interaction potential must be made a function of the distance between two deformable nuclear surfaces. Expansion of this potential to second order in the deformation parameter results in three second-order terms. One of these terms can cause a single phonon of excitation in each nucleus. Using this term in conjunction with a Born approximation and a square well nuclear potential, the resulting scattering amplitude for the mutual excitation is

$$f_{I,I'}(\theta) = \frac{uV_0R_0^3}{2\pi\hbar^2}\beta_I\beta_{I'}\sum_{l,m} i^l C(II'l, m-m0)C(II'l, 000) \times \begin{cases} [K_TR_0 j_{l-1}(K_TR_0) - (l-3)j_l(K_TR_0)], & l \neq 0 \\ [-K_TR_0 j_1(K_TR_0) + 4j_0(K_TR_0)], & l = 0 \end{cases}$$

where V_0 is the depth of a nuclear square well, R_0 is the interaction radius, β_I is the deformation associated with the excited level I in one nucleus, the prime refers to the excited state in the other nucleus, the $C(II'l, m-m0)$ are the vector-addition coefficients as defined by Rose,[8] and K_T is the transferred momentum. Employing the Born approximation, R_0 and V_0 may be obtained from the elastic scattering while β_2 may be extracted from the scattering to the first excited state. The theoretical curve shown in Fig. 2 uses the following parameters: $V_0 = 3.2$ Mev, $R_0 = 6.5 \times 10^{-13}$ cm, and $\beta_2 = 0.170$. The fit is as good as can be expected with the rather extreme approximations made. However, it is felt that the calculation accounts for the relatively large magnitude of this process and does show that the reaction is consistent with a 2-phonon interaction picture.

The 7.76 (0+) state is more weakly excited than the 4.43-Mev state by a factor of at least 10, and is weaker than the combined yield of the mutual excitation and 9.63-Mev state by a factor of at least 5. This weak excitation of the 7.76-Mev level has been observed in all direct inelastic scattering experiments such as (p, p'),[9] (d, d'),[10] and (α, α').[11] The inhibition of this level seems to be more than the density of final states would warrant, but can be explained in some cases by the use of fractional parentage coefficients[12] or by claiming that 0+ to 0+ transactions do not take place in first order in direct surface interactions. The present experiment was not able to test for

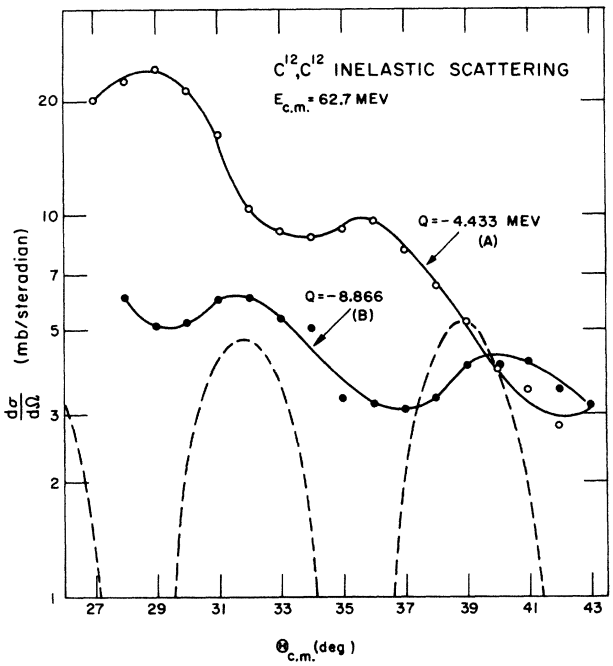

FIG. 2. Differential inelastic scattering cross sections as a function of scattering angle in the center-of-mass system. The dashed curve represents the theoretical angular distribution of the differential cross section for mutual excitation. Curve *A* and curve *B* are the experimental angular distributions for the single and mutual excitation reactions, respectively.

the inhibition of the excitation of this state via a 2-phonon process.

There is another 2-phonon surface interaction possible of the type Lemmer et al. consider, which involves the excitation in a single nucleus of a 4+ state at about 15 Mev. The existence of such a level is predicted in both the α-particle model[13] and in the shell model in intermediate coupling,[14] but has not yet been experimentally identified. In Fig. 1 there is a group corresponding to this energy but it is not clear that this group is all C^{12}, much less C^{12} with a 4+ excitation involved. Further work is being undertaken to determine the nature of this excitation.

The authors would like to thank Professor E. R. Beringer and Professor D. A. Bromley for their interest in this work.

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