from what you said, like a sudden approximation. In other words, it is only valid when you have very fast deuterons. But you have very low energies. The diffraction disintegration should be calculated by another method, not Glauber's.

UDO: Let me say that 26 MeV is just the intermediate state between a sudden approximation and adiabatic approximation. Very bad, it is true. Furthermore, in the case of Glauber's approximation, I tried to include some finite times and to include internal motion and absorption probabilities of one particle when it originally missed the nucleus. Even then, because of the internal momentum, one of the two can be absorbed. This gives amazing reduction factors for the cross sections; a factor of 10, for instance. This is only one reduction factor. Another reduction factor comes from the process itself when you include a realistic fall-off of the nuclear potential. When you have a sudden cutoff you have a value of say 200 millibarns for the process. With a smooth cutoff and time effects included the calculated cross section is down to about 10 millibarns. So there is a second argument against the occurrence of the diffraction process.

PHILLIPS: What is the magnitude of the absolute cross section here, and how does that cross section compare to ordinary nuclear cross sections? The reason I ask that is that if the ordinary cross section is comparable in your peak, then clearly one must also include the possibility of nuclear reaction in a more subtle way.

UDO: The peak cross section we have measured was 1 barn per steradian, far above any nuclear n–p correlation cross section.

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Study of the $Ca^{40}(\alpha, 2\alpha)$ Reactions*

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The correlations in energy and angle of the alpha particles produced by the reaction $Ca^{40}(\alpha, 2\alpha)Ar^{36}$ have been measured for incident alpha energies of 28.7 and 30.5 MeV. Data were taken with a two-dimensional pulse-height analyzer for an angular range from 20° to 135° with solid-state detectors (angular aperture ±2°) confined to the reaction plane. It was found that the first excited state (1.97 MeV) in Ar^{36} is much more strongly populated than the ground state. Pronounced structure was observed in practically all correlation spectra taken. At the higher incident energy and at detector angles of 35°–35° and 55°–55° with respect to the beam, the alpha particles were found to be emitted preferentially with equal energies. When the incident energy was lowered, one alpha-particle energy remained constant. This implies a two-step process via an excited state in Ca^{40} near 18.8 MeV. Measurements with unequal detector angles were carried out to determine alpha correlations with respect to the recoil axis. The experimental results will be discussed with reference to both direct and sequential reaction mechanisms.

Our study was originally undertaken with the idea of looking for something similar to the quasi-elastic reactions seen at higher energies in the $(p, 2p)$ reactions. Although there may not be justification for such an idea, this was our first outlook.

The experimental arrangement for most of the experiment was as follows: Roughly 20 nA of 30.5-MeV alpha particles from the MIT cyclotron were brought to a focus on an approximately $\frac{1}{2}$-mil-thick self-supporting, natural calcium target. The beam spot size at the target was 1 mm² and the angular divergence of the beam was less than 1°. Defining slits were circular in aperture, subtending approximately $\pm 2\frac{1}{2}°$ from the target, or about 5×10^{-3} sr. The scattered charged particles were detected by two Nuclear Diode 500-μ surface barrier detectors. The energy resolution arising from beam energy spread, kinematic broadening, and detector noise was less than about 200 keV, which was considerably less than the energy per channel for the analyzer, ∼500 keV.

The signals from the detectors are fed through a pair of Tennelec preamplifiers, through attenuators, through Sturrup linear amplifiers, and then to a Nuclear Data 4096 multichannel analyzer. The same signals which are fed into the analyzer are also put into Sturrup discriminators[1] whose coincidence output was used for the coincidence input on the 4096 analyzer.

Data for one pair of angles was collected for typically 3 h, then transferred to paper tape, and then to type-

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[1] Robert L. Chase, Rev. Sci. Instr. **31**, 945 (1960).

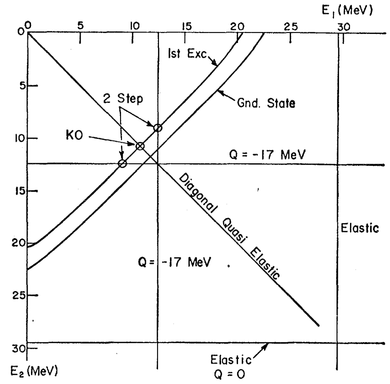

FIG. 1. General kinematics.

writer. The memory of the 4096 was so arranged that this typeout made sense. Figure 1 shows the layout for the output. The direction perpendicular to the drawing represents counts in a given channel—horizontal energy for one alpha, vertical energy for the other. The 45° line represents the locus for $(\alpha, 2\alpha)$ reactions leading to a final state in Ar^{36} of definite energy with the requirement of equal angles. If the energy lost to recoil of the Ar^{36} is neglected this line represents $E_1+E_2=$constant. The slight curving at the ends is due to the recoil. When the angles are not equal the locus is no longer a 45° line.

At this point, let us introduce some terminology which will be later useful when referring to the incident and outgoing alpha particles. α will designate the incident alpha, α' will designate the alpha particle that might be envisioned as the incident alpha inelastically scattered, and α'' will designate the second

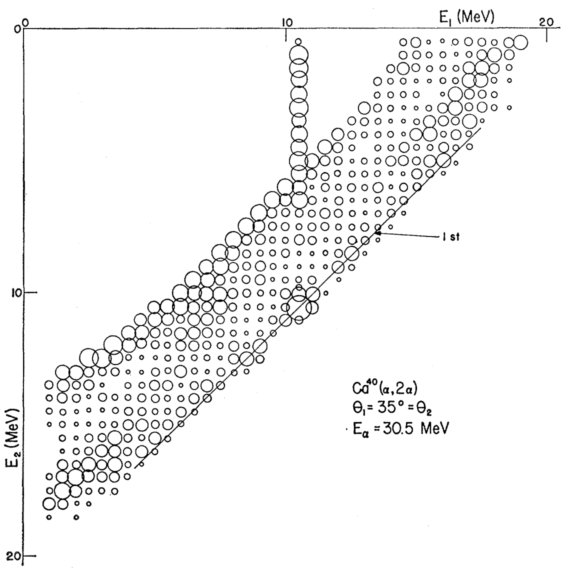

FIG. 2. Data taken with $\theta_1=35°=\theta_2$ incident α energy of 30.5 MeV.

alpha whether it is the result of a decay of an excited state or from some kind of knock-out process.

If the reaction one is interested in is a two-step process that is an (α, α') inelastic scattering followed by an α'' decay, the first step specifies the kinematics described by the vertical line. The point at which these two lines cross specifies the locus for a two-step process leaving Ar^{36} in the state mentioned before.

If instead the reaction is an α'' knock-out process and if the α'', while in the nucleus, is in an s state then one would be led to expect that the reaction would lead to events clustered along the diagonal and lying on the general kinematic line, the 45° line.

Figure 2 shows the data from a run with the angles to the two detectors equal and at 35°. All data shown will be for this pair of angles though many different pairs will be used. The areas of the circles are propor-

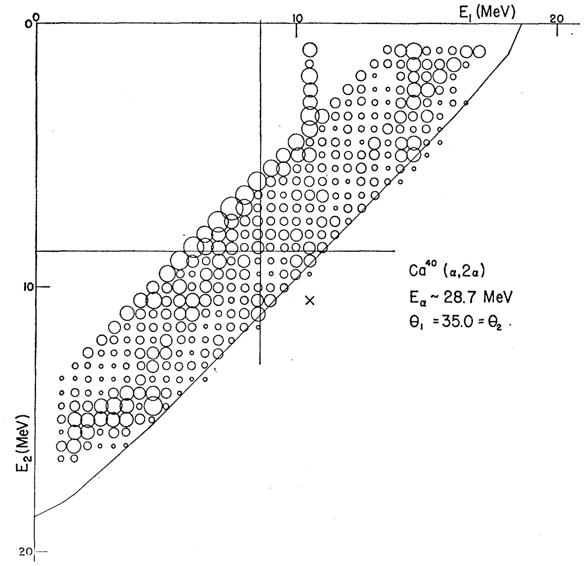

FIG. 3. Data taken with $\theta_1=35°=\theta_2$ incident α energy of 28.7 MeV.

tional to the counts in the given channels. The 45° line is for the Q value corresponding to the first excited state in Ar^{36}.

This display is 64×64, each channel corresponding to about 500 keV. The energy zero corresponds very nearly to channel zero. One could see, although not in this figure, elastic alpha particles in chance coincidence or along the edges, where for a short time the coincidence requirement was removed. Identification of the elastic scattering with this channel determined the energy scale. Note also that the elastic–elastic coincidence combined with the singles spectra can give us an estimate of the chance coincidence rate throughout the E_1E_2 plane.

A 45° line is immediately seen. When the kinematic lines corresponding to the various states of Ar^{36} are computed, it is found that this line corresponds to the first excited state, not the ground state. For all angles tried this continues to hold true. The first excited state was strongly excited whereas the ground state was hardly excited at all.

The Q values for $Ca^{40}(\alpha, \alpha p)K^{39}$ can lead to somewhat similar kinematic 45° lines. To investigate this possibility a 7-mil aluminum absorber was placed in front of one of the detectors. This absorber would reduce the energy of a 21-MeV α particle to 5 MeV, and that of a 10-MeV proton to 8 MeV. Thus, if the reaction is $(\alpha, \alpha p)$ the kinematic line will be only slightly shifted for that half of the events in which the proton is the particle passing through the degrader. In the $(\alpha, 2\alpha)$ reaction the effect of the strong degrading will sharply cut the events observed by much more than half. This latter case was observed so $(\alpha, 2\alpha)$ is indeed predominantly seen.

Finally note that there appears to be a peak along the diagonal for this first excited state line. We would initially interpret this as evidence for a knock-out process. The peak in the center was often seen when the angles were equal.

In an attempt to determine whether we are seeing knock-out or two-step we degraded the beam with 2 mils of Be. This should degrade the beam energy by about 1.8 MeV to 28.7 MeV. By observing the shift of the Ca^{40} elastic alpha we found a shift of about 2 MeV. Figure 3 shows the data taken with the absorber. Again the angles were 35° and 35°. The position of the peak from Fig. 2 is marked with an $\times$. It is seen that the previous single peak has broken into two peaks. This would not be expected from our simple view for knock-out reactions where we would have expected the peak still to be on the diagonal. The counts on the diagonal are fewer than in the peaks by 4 to 1. The 45° line in the figure is the kinematic line which would be expected for incident alpha energy of 28.7 MeV, leaving the Ar^{36} in the first excited state. The vertical lines are the inelastic (α, α') kinematics on calcium for $Q=-19$ MeV. We see that the positions of the peaks here are appropriate for the two-step hypothesis, and this is in fact the main evidence for such a conclusion.

With this assumption we may inquire about the energies of the states involved. Figure 4 shows the relevant spectra of Ca^{40}, Ar^{36}, and K^{39}. The "state" which is excited by the first step is found to have about 19-MeV excitation in Ca^{40}. The α' then has about 10.5 MeV at 35°. This "state" can then decay to the first excited state in Ar^{36} putting 10.5 MeV into the α'' at this angle. It should be noted that a state so highly excited is also proton and neutron unstable.

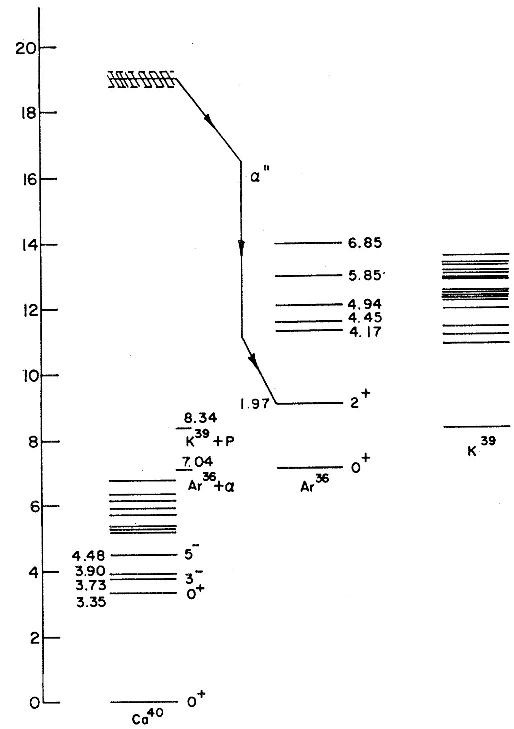

FIG. 4. Spectra of Ca^{40}, Ar^{36}, and K^{39}.

To review the results of the experiment, we seem to have seen an $(\alpha, 2\alpha)$ reaction which is sequential or two-step. The first step of this reaction leads to a "state" in Ca^{40} with $\sim$19-MeV excitation; the second step observed is alpha decay which preferentially populates the first excited state, as opposed to the ground state, of Ar^{36}.

The difficulties encountered in the experiment so far have been the very slow data collection rate, and the problem of protons and perhaps other charged particles confusing the data. We hope in the near future to remedy these problems by (1) increasing the solid angle of both detectors by perhaps as much as 10, i.e., data collection 100 times faster, and (2) particle identification using thin dE detectors and $dE\times E$ multiplication. With these improvements angular correlation measurements should prove much less ambiguous and more meaningful than the ones we have so far been able to obtain.