A106, 177 (1968).
[12]A. de-Shalit and I. Talmi, *Nuclear Shell Theory* (Academic Press Inc., New York, 1963), p. 405.
[13]de-Shalit and Talmi, Ref. 12, p. 128.
[14]F. C. Erné, Nucl. Phys. 84, 91 (1966).
[15]A. M. Moinester and W. P. Alford, Nucl. Phys. A144, 305 (1970).
[16]S. P. Pandya, Phys. Rev. 103, 956 (1956).
[17]J. R. Erskine, Phys. Rev. 149, 854 (1966).
[18]A. M. Bernstein and E. P. Lippincott, Phys. Rev. Letters 17, 321 (1966).
[19]A. Tellez, R. Ballini, J. Delaunay, and J. P. Fouan, Phys. Rev. Letters 29B, 655 (1969).
[20]L. Zamik, Phys. Letters 19, 580 (1965).
[21]J. B. French and M. H. MacFarlane, Nucl. Phys. 26, 168 (1961).
[22]F. Pellegrini, Nuovo Cimento 48B, 155 (1967).
[23]T. Yamazaki, M. Kondo, and S. Yamaba, J. Phys. Soc. Japan 18, 620 (1963).
[24]E. Gadioli and I. Iori, Nuovo Cimento 51B, 100 (1967).
[25]J. John, C. P. Robinson, J. P. Aldridge, and R. H. Davis, Phys. Rev. 177, 1755 (1969).
[26]A. Marinov, L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. 145, 852 (1966).
[27]L. Rosen, in *Proceedings of the International Conference on Polarization Phenomena of Nucleons, Karlsruhe, 1965*, edited by P. Huber and H. Schlopper (W. Rosch and Company, Bern, Switzerland, 1966), p. 253.
[28]N. Lawley, N. Dawson, G. D. Jones, I. G. Main, P. J. Mulhern, R. D. Symes, and M. F. Thomas, Nucl. Phys. A159, 385 (1970).

PHYSICAL REVIEW C VOLUME 4, NUMBER 1 JULY 1971

Stopping of 1- to 1.8-keV ^{73}Ge Atoms in Germanium*

K. W. Jones and H. W. Kraner
Brookhaven National Laboratory, Upton, New York 11973
(Received 22 March 1971)

Measurements of the amount of energy lost to ionization in the stopping of low-energy ^{73}Ge atoms, produced by inelastic neutron scattering in a germanium γ-ray detector, have been extended down to energies of about 1 keV. The results are about 35% higher than theoretical values of the Lindhard theory found from an extrapolation to this energy region. The energy of the ^{73}Ge third excited state was measured for this experiment and found to be 68.752 $\pm$0.007 keV.

I. INTRODUCTION

The amount of ionization produced in the stopping of a heavy atom has been studied theoretically by Lindhard *et al.*[1] A number of experimental measurements[2-5] have been made for the particular case of Ge atoms stopping in a germanium crystal with the energy of the Ge atoms ranging from 10 keV to 1 MeV. The agreement of these measurements with theory is reasonable over the entire range of energies.

In order to search further for deviations from the theory it seems reasonable to try to carry out measurements at very low energies. This should be a good test of the validity of the theoretical calculations at low energies, and it should be a sensitive indicator of any threshold of channeling effects in the ionization process. We have previously shown[5] that if threshold effects occur, they may be important for recoil energies of 2 to 5 keV or less but are not important at higher energies.

In the present paper, we present the results of measurements at about 1-keV germanium ion energy and compare the results with the theoretical predictions of Lindhard *et al.*[1] Some new information on the level schemes of ^{73}Ge and ^{73}As is also presented as a by-product of the primary experiment.

II. EXPERIMENTAL TECHNIQUE

Much of the experimental technique used in the present experiment has been described in our previous papers.[3-5] This experiment is mainly made possible by the great improvement in the resolution of lithium-drifted germanium detectors at low energies resulting from recent improvements in fabrication and in electronics. Since, in stopping, a 1-keV atom should lose about 200 eV of its energy to ionization and the balance to atomic scattering, excellent resolution is a *sine qua non* for a successful experiment.

The 1-keV Ge atoms were produced by the inelastic scattering of neutrons from the third excited state of ^{73}Ge. Figure 1 shows the variation of recoil energy with incident neutron energy. If the experiment is carried out just over the inelastic scattering threshold, then a beam of 0.9-keV ^{73}Ge atoms, with an energy spread of ±250 eV, is obtained. At such a low neutron energy the scattering is isotropic and the mean energy corresponds to a 90° inelastic scattering. At energies which are somewhat more than the threshold energy the scattering remains isotropic and the mean recoil energy and the spread in recoil energies both increase slowly. The increase in width of the recoil distribution does not become important until it exceeds the resolution of the detector.

The technique used to observe the stopping of the 1-keV germanium atoms was then the following. Neutrons of a suitable energy from the ^{7}Li-$(p,n)^7$Be reaction at an angle of 120° were used to irradiate a 1-cc high-resolution Ge(Li) γ-ray detector. The detector served as the source of germanium in which the inelastic scattering took place. It was placed 6 cm from the neutron source at an angle of 120° to the incident beam. Inelastic scattering events to the 69-keV third excited state then produced an approximately monoenergetic recoil atom as well as the γ ray produced in the decay of the excited state. The ionization produced in the detector is the sum of the ionization produced by the two individual events. If we compare the resulting peak in a pulse-height distribution with suitable calibration peaks, then the total energy of the two events can be deduced. If the energy of the excited-state γ ray is known, the amount of ionization produced by the Ge recoil is given by the difference of the two energies. This procedure assumes that an energy calibration deduced from γ- and x-ray sources can be applied to the ionization from the germanium recoil.

It soon became apparent during the experiment that the energy of the state of interest in ^{73}Ge listed in the literature was seriously in error. This early value had been found by Chupp *et al.*[6] to be 67.03 ± 0.010 keV by observation with a bent-crystal spectrometer of the γ rays produced in the proton bombardment of ^{73}Ge. We made a series of measurements with both Ge(Li) and Si(Li) detectors which utilized the ^{72}Ge$(n,\gamma)^{73}$Ge*, ^{73}Ge(α,α')-^{73}Ge*, and ^{73}Ge$(p,p')^{73}$Ge* reactions to produce the γ ray. An average of these measurements, which are summarized in Table I, gives a value of 68.752 ± 0.007 keV for the energy of the third excited state of ^{73}Ge. The energy calibration was made relative to the 59.537 ± 0.001-keV ^{241}Am γ ray[7] and Pb K x rays at 72.8042 and 74.9694 keV,[8] which were fluoresced by a ^{57}Co source. A typical spectrum is shown in Fig. 2 for the proton bombardment of ^{73}Ge observed with a Si(Li) detector.

TABLE I. Summary of measurements of energy of the ^{73}Ge third excited state.

Reaction	γ-ray energy (keV)
^{73}Ge$(p,p'\gamma)^{73}$Ge	68.751 ± 0.018
	68.740 ± 0.018
	68.748 ± 0.018
	68.747 ± 0.018
^{72}Ge$(n,\gamma)^{73}$Ge	68.746 ± 0.018
^{73}Ge$(\alpha,\alpha')^{73}$Ge	68.759 ± 0.018
	68.773 ± 0.018
Mean value: with external error	68.752 ± 0.004
internal error	68.752 ± 0.007
Adopted value	68.752 ± 0.007

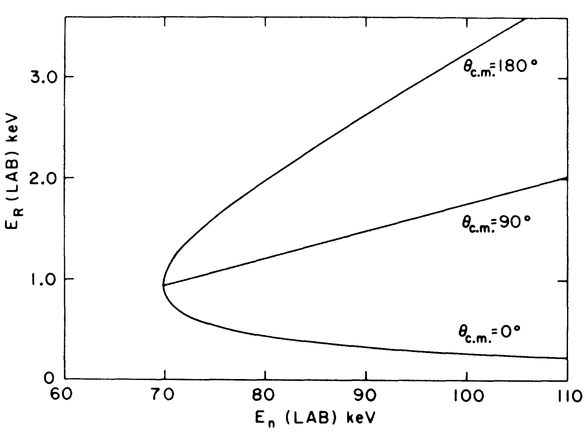

FIG. 1. Kinematics for the ^{73}Ge$(n,n_3)^{73}$Ge* reaction. The energies for the ^{73}Ge* recoil nucleus are shown for center-of-mass scattering angles of 0, 90, and 180° as a function of incident neutron energy. The mean recoil energy is given by the 90° line.

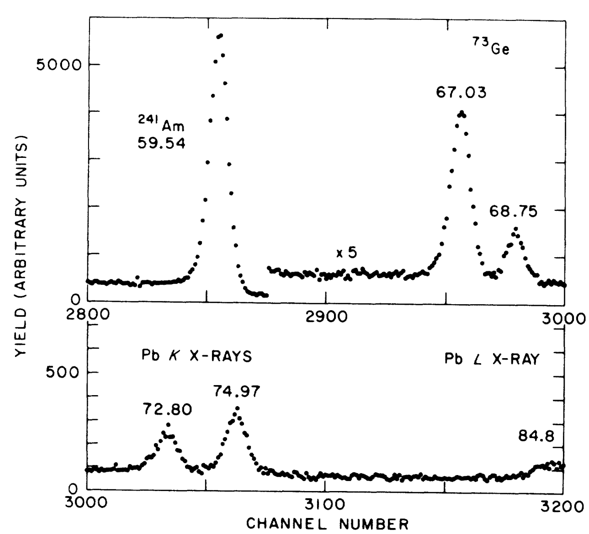

FIG. 2. Pulse-height spectrum observed with a Si(Li) γ-ray detector for the γ rays at ~68-keV energy produced by the bombardment of ^{73}Ge with 3.12-MeV protons. The ^{241}Am γ ray and Pb x rays used for calibration are also shown.

The proton energy was 3.12 MeV.

The 67.03-keV line reported by Chupp *et al.*[6] was also observed, but only in the proton bombardment of ^{73}Ge. The intensity of the 68.75-keV line is only 15% of the 67.03-keV line which explains why it was not seen by Chupp *et al.*[6] The assignment of the 67.03-keV line must be to the ^{73}Ge$(p, n)^{73}$As* reaction and is in good agreement with the recent result of 66.9 ± 0.5 keV given by Rao and Fink.[9] A summary of the low-lying energy levels of ^{73}Ge and ^{73}As in light of these results is shown in Fig. 3. We note from Fig. 2 that the 75.7-keV level of ^{73}As observed[9] in the decay of ^{73}Se was not seen.

A problem arising in the main part of the experiment, the measurement of the energy of γ-ray-plus-recoil ionization just above threshold, is the finite cross section for production of the state by the ^{72}Ge$(n, \gamma)^{73}$Ge* reaction. This is evidenced by production of the line at neutron energies below the $(n, n'\gamma)$ threshold. Measurements of the yield below threshold as a function of distance between counter and target showed that the main contribution was from neutrons direct from the target and not from a generalized room neutron background.

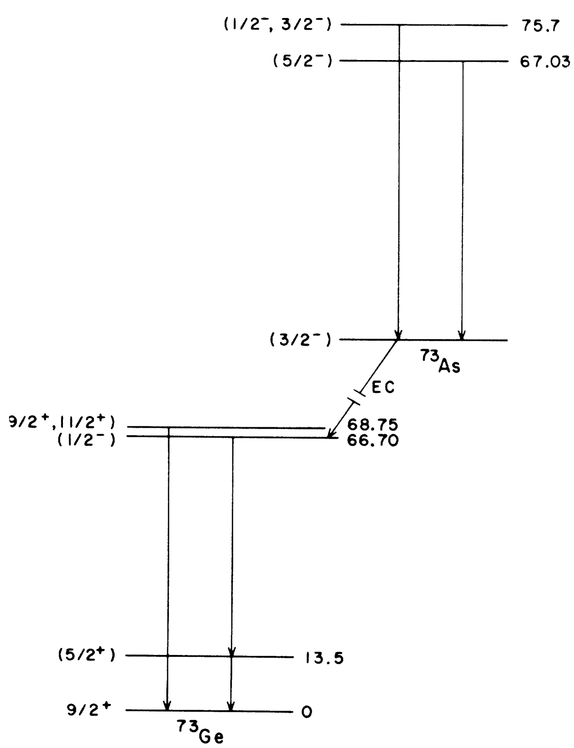

FIG. 3. Energy level diagram showing the low-lying levels of ^{73}As and ^{73}Ge. The diagram is based on the present results as well as the summary shown in Nucl. Data B1 (No. 6), 48 (1966), and the work of D. G. Douglas [Can. J. Phys. 47, 1813 (1969)] on the decay of ^{73}As.

Elaborate shielding of the detector was therefore not necessary. The energy of the line was about 300 eV greater than the level energy. For the thermal-capture case, the maximum possible energy given to the Ge recoil from γ-ray emission is 0.339 keV. This energy can be less, depending on the various cascade deexcitations and the lifetimes of the states compared with the stopping time of the recoil germanium nucleus. If the mean energy of the captured neutron is greater than zero, the kinetic energy of the product nucleus will increase by $\frac{1}{73}$ of that amount. Thus, the energy of a ^{73}Ge nucleus produced by the capture reaction can be comparable to the recoil energy of the nucleus when produced in the ^{73}Ge-(n, n') reaction, and the contribution of the capture reaction must be considered.

In part, the choice of angle of 120° for neutron production was dictated by the desire to eliminate the undesirable low-energy group of neutrons produced at low bombarding energies at 0° and thus reduce background from capture. The relative importance of the capture background is found by measuring an excitation curve for the yield of the 68.75-keV γ ray. This excitation curve is shown in Fig. 4.

The effect of the capture background line was investigated in most detail for the point at a recoil energy of 0.96 keV. Here the sensitivity to

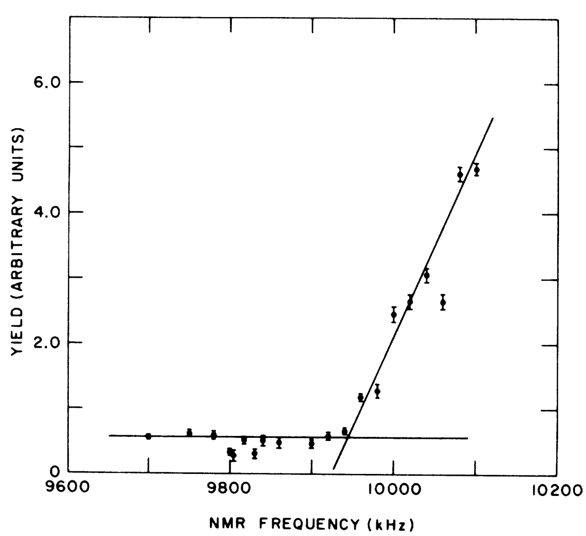

FIG. 4. Excitation curve for the ^{73}Ge$(n, n_3)^{73}$Ge* reaction. The field is given by the yield of the 68.75-keV γ ray. The NMR frequency is proportional to the incident proton momentum. The neutrons are produced by these protons in the ^{7}Li$(p, n)^{7}$Be reaction and thus the NMR frequency is closely related to neutron momentum also. The background below threshold is produced by the ^{72}Ge(n, γ)-^{73}Ge reaction. The threshold NMR frequency is consistent with the energy calibration of the electrostatic accelerator and the experimental geometry.

background is most important since the real and background rates are about equal. The position of the peak of interest was found by a least-squares fit of two Gaussian peaks and an exponential background to the data. The relative areas of the two peaks were chosen to fit the excitation curve. At higher energies, the relative background intensity becomes steadily less and does not appreciably affect the position of the ^{73}Ge(n, n') peak. The energy of the ^{73}Ge line summed with the ionization produced by the recoil was calculated for each run relative to the ^{241}Am 59.537 ± 0.001-keV γ ray and the two Pb x rays with an energy of 72.8042 and 74.9694 keV. Results were obtained at eight energies above the threshold. Typical experimental spectra above and below threshold are shown in Fig. 5.

The remaining problem is to determine the energy of the ^{73}Ge recoil atom. This is found from kinematics and the mean neutron energy. The mean neutron energy was deduced from the excitation curve shown in Fig. 4. A correction was made for the finite target thickness by assuming that the ^{7}Li$(p, n)^7$Be cross section was constant, that the ^{73}Ge$(n, n')^{73}$Ge* production cross section varied as $(E_n - E_{\text{th}})^{1/2}$, and that the angular distribution for inelastic scattering was isotropic. The final recoil energy is the recoil energy for 90° neutron scattering averaged over the neutron energy spread caused by the finite target thickness. The largest correction was about 200 eV.

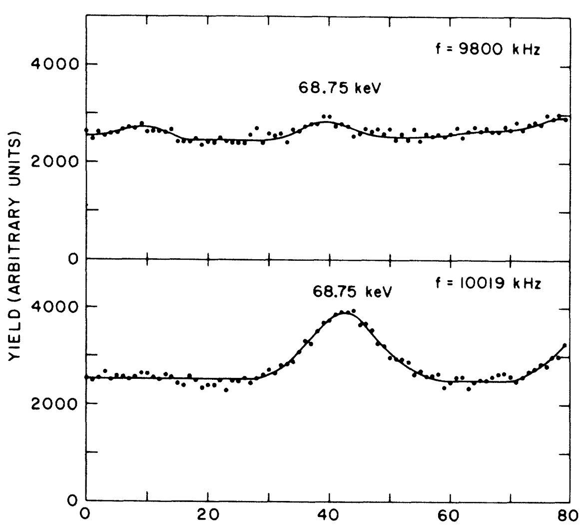

FIG. 5. Pulse-height spectra showing the 68.75-keV line produced below threshold and about 1 keV above threshold. The experimental conditions were slightly different for the two runs so that the peak positions and yields cannot be compared directly. The yield of each relative to the background shows the decrease in yield below threshold. The areas of such peaks, properly normalized, are shown in Fig. 4.

III. DISCUSSION

Figure 6 displays the energy shift of the observed line found from the difference between the peak and level energies as a function of average recoil energy. Table II lists the numerical results. Observe that all but the points at $\overline{E}_R = 0.96$ and 1.75 keV lie substantially above the values given by the Lindhard theory for $k = 0.15$, where k is the electronic stopping parameter defined in Ref. 1. The uncertainties assigned represent primarily the uncertainty in the incident neutron energy (abscissa) and in deducing a line energy from an observed line shape (ordinate). A measurement at a recoil energy of 10 keV was made in this experiment by a technique based on the line shape[5] rather than the line shift. It agreed with a previous measurement using the shift of the 691-keV level in ^{72}Ge.[5] The two values are in agreement with each other and with the Lindhard theory for $k = 0.15$.

The theoretical line for $k = 0.15$, which fits the higher-energy data well, extends the Lindhard theory to the low-energy limit of the Thomas-Fermi model. Calculations using both the extrap-

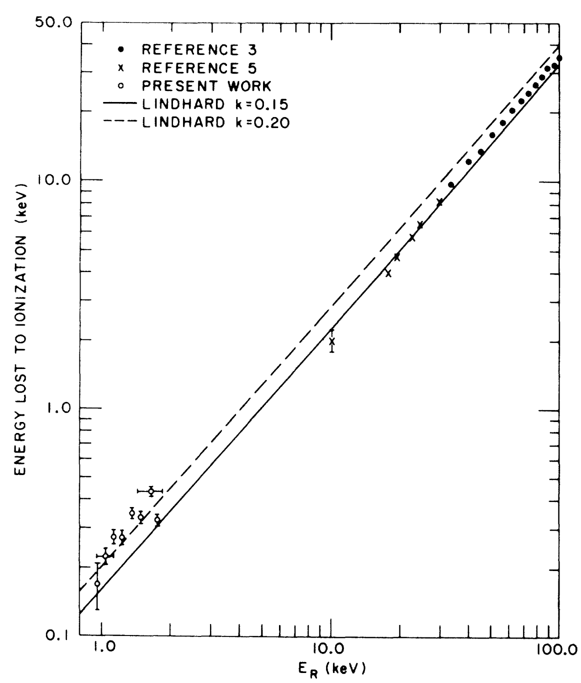

FIG. 6. Amount of ionization produced by ^{73}Ge recoil atoms as a function of their energy. The experimental points are shown as well as predictions calculated from the theory of Lindhard *et al.* for two values of the electronic stopping parameter, k. Here $k = 0.2$ gives a fair fit in the low-energy region, while for energies from 10 to 100 keV, $k = 0.15$ is better.

TABLE II. Summary of results.

Recoil energy (keV)	Energy lost to ionization (keV)
0.96 [a]	0.169 [b]
1.04	0.224
1.12	0.276
1.22	0.272
1.35	0.349
1.48	0.334
1.62	0.435
1.75	0.326

[a]Uncertainty for all the recoil energies is estimated at ±0.2 keV at $E_R = 1.75$ keV and at ±0.1 keV at $E_R = 1.04$. The relative uncertainty is estimated to be ±0.05 keV.

[b]Uncertainty is ±0.020 keV for all but the $E_R = 0.96$-keV point where it is ±0.04 keV.

olations of Eq. (5.2) of Ref. 1 and of the computation displayed in Fig. 3 of the same reference do agree at ϵ, the Lindhard dimensionless energy parameter,[1] as low as 10^{-3} or $E_R = 0.28$ keV. A better fit to the low-energy data is obtained for $k = 0.20$, possibly indicating a trend to higher k values at low energies. An increase in the electronic fraction of energy loss might also be explained at low energy if a large fraction of recoils scattered at random with respect to channel directions were channeled because of the increasingly large acceptance angle at lower energy. The channeling acceptance angle[10] for 1-keV Ge ions in Ge, given a 2-Å plane spacing, is 55°, which would allow a substantial fraction of initially randomly scattered recoils to channel with enhanced electronic contributions.[11] Channeling effects are not included in the Lindhard theory.

Predictions for the straggling in ionization are also made by the Lindhard theory.[1] Our results indicate that the width of the line produced by the sum of the 68.75-keV ^{73}Ge γ ray and the Ge recoil ionization is essentially no larger than the lines produced by γ rays alone. If we assume that the width of the lines result from the addition in quadrature of electronic noise plus statistics for the 68.75-keV line and the fluctuations in recoil ionization, we conclude that the fluctuations are less than 450 eV. This result is consistent with the small values for the fluctuations predicted by Lindhard *et al.*[1] However, calculations have also been made by Haines and Whitehead[12] who predict that at low energies the energy dispersion is approximately equal to the energy. Their result is not supported by our present limit of 450 eV at recoil energies of ~1 keV.

Finally we note that the Lindhard theory has been shown to give good agreement with our experiments in the range from 1 to 100 keV and with other experiments at higher energies. There does appear to be some possibility that the experimental results for the ionization loss start to deviate from the Lindhard theory at energies around 1 keV. There is no evidence here for the existence of a minimum recoil energy for the production of ionization. However, this conclusion could possibly be affected if channeling were to really play an important role.

ACKNOWLEDGMENTS

We are indebted to Dr. C. Chasman for help in taking some of the data and for several discussions, and to Dr. W. R. Kane for his help in making the ^{72}Ge$(n,\gamma)^{73}$Ge measurement at the high-flux beam reactor.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1]J. Lindhard, V. Nielsen, M. Scharff, and P. V. Thomsen, Kgl. Danske Videnskab. Selskab, Mat.– Fys. Medd. 33, No. 10 (1963).

[2]A. R. Sattler, F. L. Vook, and J. M. Palms, Phys. Rev. 143, 588 (1966).

[3]C. Chasman, K. W. Jones, and R. A. Ristinen, Phys. Rev. Letters 15, 245 (1965).

[4]C. Chasman, K. W. Jones, R. A. Ristinen, and J. T. Sample, Phys. Rev. 154, 239 (1967).

[5]C. Chasman, K. W. Jones, H. W. Kraner, and W. Brandt, Phys. Rev. Letters 21, 1430 (1968).

[6]E. L. Chupp, J. W. M. DuMond, F. J. Gordon, R. C. Jopson, and H. Mark, Phys. Rev. 112, 532 (1958).

[7]R. W. Jewell, W. John, R. Massey, and B. G. Saunders, Nucl. Instr. Methods 62, 68 (1968); G. C. Nelson and B. G. Saunders, *ibid.* 84, 90 (1970).

[8]J. A. Bearden, Rev. Mod. Phys. 39, 78 (1967).

[9]P. V. Rao and R. W. Fink, Phys. Rev. 154, 1028 (1967).

[10]J. Lindhard, Kgl. Danske Videnskab. Selskab, Mat.– Fys. Medd. 34, No. 14 (1965).

[11]D. D. Moak, J. W. T. Dabbs, and W. W. Walker, Rev. Sci. Instr. 37, 1131 (1966).

[12]E. L. Haines and A. B. Whitehead, Rev. Sci. Instr. 37, 190 (1965).