tions from linearity in all cases except that of Tb^{161} are qualitatively consistent with the effect of additional neutrons coming out of either the compound nucleus or the fission fragments. The behavior of Tb^{161} suggests that some other factor is playing a significant role. Most probably the mass distrigutions associated with the basic fission modes are changing with energy.

In Paper I the exactness of the two-mode fission hypothesis was questioned because the results from thermal neutron fission of U^{235} did not fall on the corresponding lines in the R value plots. Despite this, the hypothesis appeared to serve as a good approximation at low energies even though the fission of more than one nuclear species was probably observed. The general concepts of the two-mode fission hypothesis are attractive ones and may be valid. However, it would appear that those conditions that are necessary for quantitative treatments within the framework of the hypothesis can be approximated only over limited energy ranges for a particular fissioning system.

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d-He^4 Elastic Scattering from 6 to 14 MeV*

LEONA STEWART, J. E. BROLLEY, JR., AND L. ROSEN
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
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Elastic differential cross sections for d-He^4 scattering have been measured for deuteron laboratory energies between 6 and 14 MeV. Both deuterons and alpha particles were accelerated in the Los Alamos variable-energy cyclotron and focused at the center of the Los Alamos multiplate camera. The charged-reaction products were identified on the basis of range measurements in processed $K2$ emulsions. The present results are at variance with previous work at 8 MeV and also indicate significant deviations at large angles from earlier experiments at 13.7 MeV. Around 10 MeV, previous results have been substantiated.

I. INTRODUCTION

DEUTERON–HELIUM elastic scattering has been the subject of extensive investigation at deuteron energies below 5 MeV.[1] At these energies, elastic scattering has proven to be a powerful tool for the study of low-lying excited states in the compound system, Li^6, and has shed some light on the coupling of the two p-shell nucleons. At higher energies, however, angular distribution measurements were made only at 8.0,[2] 10.3,[3] and 13.7 MeV.[4]

Although no recent experimental work has been performed on this problem, theoretical interest has continued to such an extent that a complete bibliography would be excessively lengthy. The analysis of the low-energy data[1] by Galonsky and McEllistrem[5] in 1955 and a general treatment of the deuteron (spin-one) problem by Lakin[6] and Stapp[7] have been both preceded and followed by many excellent papers on the spin polarization of the deuteron.[8]

In 1960, Gammel, Hill, and Thaler developed a

TABLE I. Estimated errors.

Y:	particle identification and counting efficiency	1.5%
n:	number of incident particles	1.0%
N:	number of target nuclei	2.0%
G:	slit geometry	1.0%
	beam energy	1.0%
	statistical	variable
	background	25% background correction
	water vapor	25% of correction where applicable

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

[1] A. Galonsky, R. A. Douglas, W. A. Haeberli, M. T. McEllistrem, and H. T. Richards, Phys. Rev. **98**, 586 (1955). References to earlier work are also given in this paper.

[2] E. J. Burge, H. B. Burrows, and W. M. Gibson, Proc. Roy. Soc. (London) **A210**, 534 (1952).

[3] J. C. Allred, D. K. Froman, A. M. Hudson, and L. Rosen, Phys. Rev. **82**, 786 (1951).

[4] R. G. Freemantle, T. Grotdal, W. M. Gibson, R. McKeague, D. J. Prowse, and J. Rotblat, Phil. Mag. **45**, 1090 (1954).

[5] A. Galonsky and M. T. McEllistrem, Phys. Rev. **98**, 590 (1955).

[6] W. Lakin, Phys. Rev. **98**, 139 (1955).

[7] H. P. Stapp, thesis, University of California Radiation Laboratory Report UCRL-3098, 1955 (unpublished).

[8] In addition to the many references given by G. R. Satchler in Oak Ridge National Laboratory Report ORNL-2861, 1960 (unpublished), an excellent treatment can be found in J. Hamilton, *The Theory of Elementary Particles* (Clarendon Press, Oxford, 1959).

TABLE II. Differential cross sections in the center-of-mass system for d-He^4 elastic scattering at various deuteron laboratory energies.

θ, c.m. angle (degrees)	$\sigma(\theta)$ (mb/sr)	Rms error (percent)
6.0 MeV		
30.2	302[a]	3
38.0	172[a]	3
46.0	109[a]	3
62.9	55.6[a]	3
72.0	47.8[a]	3
82.2	52.3[a]	3.5
114.9	74.3	3
119.9	78.7	3
124.9	90.6	3
129.9	106	3
134.9	126	3
140	147	3
145	176	3
150	211	3
155	234	3
160	254	3
6.3 MeV		
15.0	1040	4.5
18.8	563	4
22.5	448	3.5
26.2	320	3.5
29.9	286	3
33.6	229	3
37.3	185	4
41.0	148	4
44.6	122	3.5
48.2	102	3.5
51.8	84.3	3.5
55.4	68.1	4
58.9	56.4	4.5
62.4	47.4	3
65.9	44.9	3
69.3	42.4	3.5
72.7	43.0	3
76.1	46.2	3
79.4	48.9	3
82.7	50.7	3.5
85.9	56.4	3
89.1	57.6	3
92.2	60.7	3
95.2	62.2	3
98.3	66.9	3
101.2	63.5	3
104.1	63.8	3.5
107.0	66.2	4
109.7	71.2	3.5
110.0	69.5[a]	3.5
112.5	66.2	3.5
115.0	69.7[a]	3.5
115.1	66.9	3
120.0	76.4[a]	3.5
125.0	83.0[a]	5
125.1	83.6	3
130.0	93.6[a]	4
135.0	112.3[a]	3
140.0	133.2[a]	3
7.1 MeV		
30.2	255[a]	3.5
38.0	155[a]	3.5
46.0	91.0[a]	3
54.2	49.0[a]	3
62.9	35.0[a]	3
72.1	40.1[a]	3.5
82.2	54.6[a]	3.5
94.1	66.4[a]	3
114.9	59.4	3.5
119.9	57.4	3.5
124.9	59.5	3.5
129.9	69.4	3
134.9	79.9	3
139.9	98.0	3
144.9	120	3
150	148	3
155	168	3
160	198	3
7.5 MeV		
15.0	919	4
18.8	511	3.5
22.5	382	3.5
26.2	289	3.5
29.9	243	3.5
33.6	197	3
37.3	151	3.5
41.0	123	4
44.6	92.2	3.5
48.2	70.7	4
51.8	52.3	4
55.4	39.8	3.5
58.9	35.9	3
62.4	31.2	3
65.9	32.8	3
69.3	36.3	3
72.7	37.6	3
76.1	43.5	3
79.4	49.8	3
82.7	53.0	3
85.9	56.7	3.5
89.1	60.5	3
92.2	65.6	3
95.0	66.2[a]	3
95.3	66.7	3.5
98.3	64.7	3.5
100.0	70.2[a]	3
101.2	65.3	3
104.1	66.1	3
105.0	67.1[a]	3.5
107.0	63.7	3.5
109.8	63.1	3
110.0	61.0[a]	3.5
112.5	59.2	3.5
115.0	59.5[a]	3.5
115.1	60.9	3
120.0	56.4[a]	3.5
125.0	53.8[a]	4.5
130.0	57.5[a]	4.5
135.0	72.7[a]	3.5
140.0	88.9[a]	3
8.5 MeV		
30.2	198[a]	3.5
38.0	114[a]	3.5
46.0	63.8[a]	3
54.2	26.8[a]	3
62.9	20.6[a]	3
72.1	30.9[a]	3
82.2	51.7[a]	3
94.1	66.0[a]	3.5
114.9	52.5	3
119.9	44.3	3
124.9	44.7	3
129.9	45.1	3
134.9	46.5	3
139.9	58.2	3
141.0	60.9[a]	4
144.9	70.9	3
147.9	82.9[a]	3
149.9	93.5	3
153.0	102[a]	3
154.9	103.0	3
160.0	132	3
8.8 MeV		
15.0	763	4
18.8	443	4.5
22.5	327	3.5
26.2	254	3.5
29.9	206	3
33.6	161	3.5
37.3	122	3.5
41.0	89.1	3.5
44.6	64.0	3.5
48.2	45.5	3.5
51.8	31.5	4
55.4	22.8	3.5
58.9	19.2	4
62.4	17.6	4
65.9	21.8	3.5
69.3	23.7	4.5
72.7	32.2	4
76.1	37.7	3.5
79.4	45.2	3
80.0	46.3[a]	3.5
82.7	51.3	3
85.0	50.7[a]	4
85.9	53.3	3.5
89.1	62.1	3
90.0	62.4[a]	3
92.2	66.1	3
95.0	63.7[a]	3.5
95.3	65.5	3
98.3	68.6	3
100.0	67.9[a]	3.5
101.2	63.1	3.5
104.1	66.3	3
105.0	60.7[a]	4
107.0	60.6	3.5
109.8	54.3	4
8.8 Mev		
110.0	58.8[a]	3
112.5	54.2	4
115.0	48.5	4
115.1	48.3	4.5
120.0	45.4[a]	3.5
125.0	43.0[a]	3.5
130.0	43.0[a]	4
135.0	49.1[a]	3
140.0	54.0[a]	3.5
10.0 MeV		
15.0	638	4
22.5	334	3.5
38.0	99.7	3.5
46.0	44.3	4
54.3	15.5	3.5
58.9	9.8	5.5
62.9	12.6	3.5
72.1	27.2	3.5
79.4	42.8	3.5
114.9	50.1	4.5
119.9	43.2	3.5
124.9	36.2	3.5
129.9	32.8	4
134.9	32.6	3.5
139.9	38.6	4
144.9	51.7	3.5
149.9	59.8	3.5
154.9	77.5	3.5
160.0	94.1	3.5
12.0 MeV		
15	568	4
18.8	379	4
22.5	309	4.5
26.2	227	3.5
30	183	3.5
33.6	125	3.5
37.3	88.7	4
38.0	73.9[a]	3.5
41.0	62.7	3.5
44.6	38.4	4.5
46.0	29.8[a]	3.5
51.8	11.0	5.5
54.3	8.3[a]	3.5
58.9	5.9	8
62.9	9.38[a]	3.5
65.9	12.3	4.5
72.1	23.4[a]	3.5
72.8	24.8	4.5
79.4	38.8	4
82.2	44.5[a]	3.5
85.9	54.7	4
90.0	54.8[a]	3.5
94.2	57.3[a]	3
100.0	58.9[a]	3.5
105.0	55.7[a]	3.5

[a] Alpha particles.

TABLE II (*continued*).

θ, c.m. angle (degrees)	$\sigma(\theta)$ (mb/sr)	Rms error (percent)
12.0 Mev		
110.0	49.8[a]	3.5
115.2	44.6	4.5
120.0	36.9[a]	3.5
125.0	29.5[a]	4
130.0	28.2[a]	3.5
135.0	26.9[a]	3.5
140.0	29.3[a]	4
142.2	29.8	4.5
147.9	36.8[a]	4
153.0	47.1[a]	3.5
157.2	55.2[a]	3.5
160.4	65.7	4.5
164.6	71.8	5.5
167.3	78.6	3
171.2	88.5	3.5
173.8	90.0	3.5
176.3	91.4	3.5
13.7 MeV		
15.0	584	4
18.8	414	4
22.5	337	4
26.2	251	3.5
30.0	184	4
33.7	125	4
38.0	70.4[a]	3.5
41.0	49.5	8
46.0	25.3[a]	3
54.3	8.02[a]	3.5
13.7 Mev		
62.9	10.4[a]	4.5
72.1	24.2[a]	3.5
76.1	30.4	8
79.4	37.2	5.5
82.2	41.3[a]	3.5
85.9	46.9	5
90.0	51.3[a]	3
95.0	50.2[a]	3.5
95.3	52.1	4.5
100.0	54.4[a]	3
105.0	48.7[a]	3.5
110.0	41.0[a]	4
115.2	37.9	4
120.3	30.8	4.5
125.0	26.8[a]	3.5
129.8	23.2	4
135.0	20.3[a]	4.5
140.0	23.7[a]	3.5
144.1	26.1	5.5
147.9	30.0[a]	3.5
149.4	29.4	6.5
153.0	36.9[a]	4
154.3	39.0	4.5
157.2	45.8[a]	3.5
158.9	48.5	5
163.2	54.8	4
167.3	55.9	5
171.2	63.6	4.5
176.3	68.8	4.5

model[9] for the d-He^4 system which they used to phase shift analyze the 8- and 10.3-MeV data. From this analysis they predicted large polarizations. One of the present authors (L. R.) looked for these effects by measuring the asymmetries produced in the double scattering of deuterons by helium in the region from 8 to 10 MeV and found them to be quite small. When a subsequent measurement of the elastic scattering at 8 MeV indicated large deviations from previously published data, a detailed study of the elastic scattering angular distributions from 6 to 14 MeV was initiated.

II. EXPERIMENTAL PROCEDURE

Deuterons and alpha particles were accelerated in the Los Alamos variable-energy cyclotron and focused at the center of the Los Alamos multiplate camera. The target gas (helium and deuterium, respectively) filled the scattering chamber and each angle of observation (10° to 172.5°) was well defined by means of a precision slit system. The charged-reaction products were identified on the basis of range measurements in the processed emulsions. Details on gas handling, current integration methods, and the camera geometry can be found in previous papers,[10] and the general experimental techniques described therein were employed here.

In d-He^4 scattering, other charged particles are observed (at these incident energies) from the following

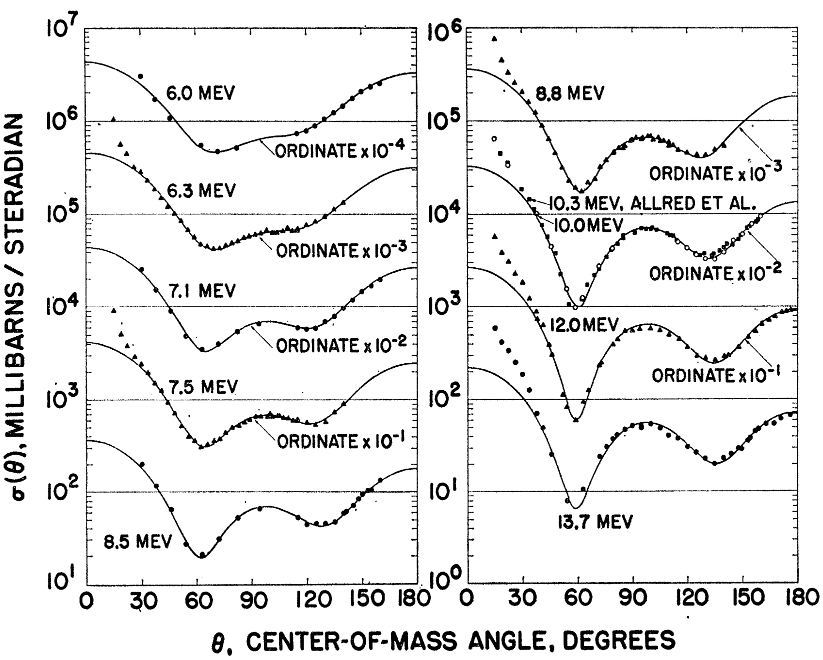

FIG. 1. Differential cross section in the center-of-mass system for d-He^4 elastic scattering. The smooth curves represent Legendre fits to the data above 30°. At 10 MeV, the results of Allred *et al.* (reference 3) (at 10.3 MeV) were included in the fits but the present data were more heavily weighted.

[9] J. L. Gammel, B. J. Hill, and R. M. Thaler, Phys. Rev. **119**, 267 (1960).
[10] J. C. Allred, L. Rosen, F. K. Tallmadge, and J. H. Williams, Rev. Sci. Instr. **22**, 191 (1951).

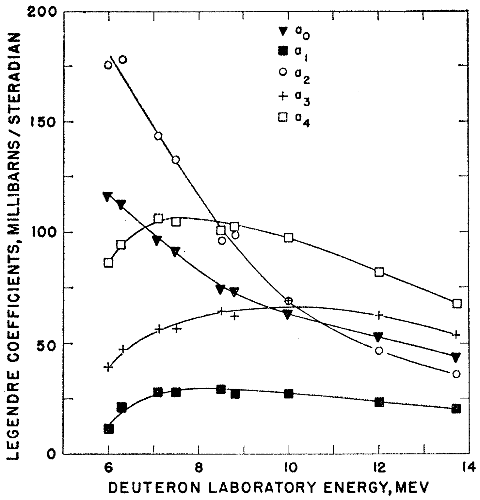

FIG. 2. Legendre coefficients vs deuteron laboratory energy for d-He^4 elastic scattering.

reactions:

(a) $d+He^4 \rightarrow n+p+He^4$,

(b) $d+He^4 \rightarrow p+He^5$, (and $p+He^{5*}$) $\searrow n+He^4$,

(c) $d+He^4 \rightarrow n+Li^5$, (and $n+Li^{5*}$) $\searrow p+He^4$.

Since for every reaction which takes place, both a proton and an alpha are emitted, care must be taken to ioslate the ranges of the elastically scattered deuterons and alpha particles. In order to maximize the angular range of the measurements, both deuterons and alpha particles were used as the incident particles.

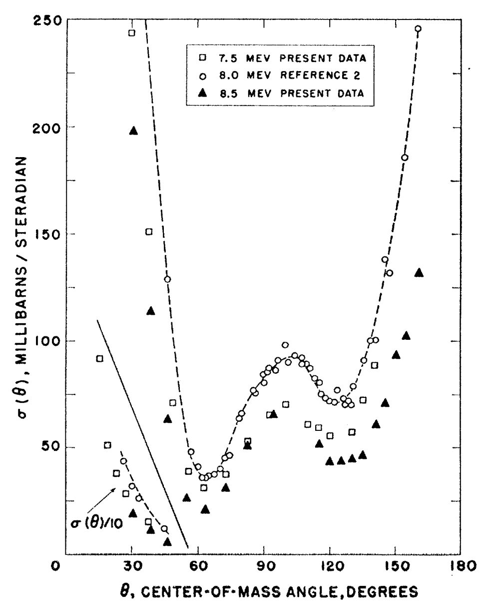

FIG. 3. Comparison of the data near 8 MeV. The smooth curve is drawn through the points of reference 2.

III. CALCULATION OF THE CROSS SECTIONS AND EVALUATION OF ERRORS

The differential cross section is obtained from

$$\sigma(\phi) = Y(\beta)/nNG(\beta),$$

where $Y(\beta)$ is the measured yield incident on the emulsion surface at lab angle β, n is the number of incident particles in the beam, N is the number of target nuclei, and $G(\beta)$ is obtained from integrating over the reaction volume at angle β. All of the above contribute to the uncertainty in the measured value $\sigma(\beta)$ in the following manner:

Since particle yield must be established absolutely on the basis of range, a large peak-to-background ratio is mandatory. It was found, for instance, that for 10-MeV deuterons on He^4, protons from the ground-state reaction (b) had the same range as the elastically scattered deuterons (at large angles). The associated backgrounds were, in these instances, more difficult to evaluate. At this energy, data for the same center-of-mass angular region were, therefore, obtained by analyzing the emulsions exposed when He^4 was the accelerated particle and deuterium the target. In most cases, however, the associated background is $<4\%$ and no data were used if the background exceeded 10%. Errors in evaluating this correction are included in the rms error at each angle.

A contaminant in the form of water vapor was present in the target gas in three of the runs. The scattered particles were observed, identified, and counted in order to calculate this impurity. Corrections were made to the data (at a few angles where range separation of the particles was impossible) and the errors were again increased accordingly. The uncertainties listed in Table I, when combined quadratically, give the errors tabulated in Table II.

It should be noted that the uncertainty associated with the water vapor applied at three energies only. In

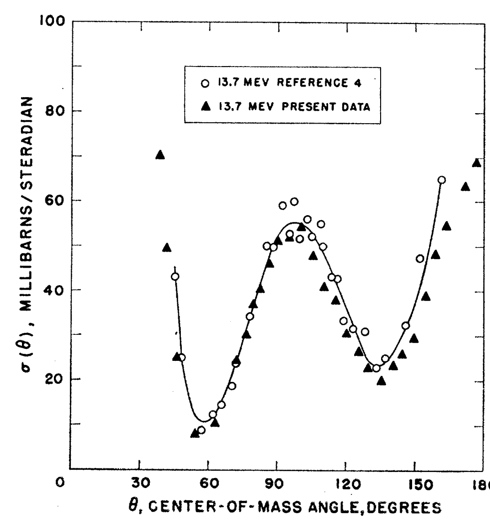

FIG. 4. Comparison of the 13.7-MeV data. The smooth curve is drawn through the points of reference 4.

addition, the low backgrounds observed in the majority of cases necessitated very small background corrections.

IV. RESULTS

The differential cross sections as a function of angle are shown in Fig. 1 for each (equivalent) deuteron laboratory energy. Since the 90° cross section is essentially constant with energy, each ordinate is offset in order to show the individual data points. The data at 10.3 MeV of Allred *et al.*[3] are plotted for comparison. The smooth curves were obtained from a least-squares fit to the data above 30° using Legendre polynomials of order 4. The Legendre coefficients as a function of energy appear in Fig. 2.

The differential cross sections in the center-of-mass system are tabulated with the rms error for each deuteron energy in Table II. Figure 3 displays a comparison with the 8-MeV data[2] of Burge *et al.* Since the differences between the two sets of data are often several times the standard deviations, a few points from the 7.5- and 8.5-MeV data are also shown. The latter tend to verify the self-consistency of the present results. Although it is seen that the positions of the maxima and minima agree very well between the three sets of data near 8 MeV, no constant multiplying factor can be found to bring them into agreement. The 13.7-MeV data[4] of Freemantle *et al.* are compared with the present measurements in Fig. 4. Here the agreement is fair, except at large angles.

ACKNOWLEDGMENTS

We are indebted to the cyclotron group for providing the appropriate beams for these experiments. We wish, also, to express our appreciation to the nuclear plate group for the large amount of plate reading which was accomplished, and, in particular, to Mrs. Rexine Booth who supervised much of the plate analysis work and data reduction. Finally, we wish to acknowledge the contribution of Mrs. Opal Milligan in processing the hundreds of emulsions utilized in the present experiments.

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Recoil Study of the Reaction $C^{12}(p,pn)C^{11}$†

SARJANT SINGH AND JOHN M. ALEXANDER
Lawrence Radiation Laboratory, University of California, Berkeley, California
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Recoil ranges of C^{11} from the reaction $C^{12}(p,pn)C^{11}$ are presented for incident proton energies from 0.25 to 6.2 GeV. From these data it is concluded that a neutron evaporation mechanism is probably not the major mechanism. The results are consistent with a fast reaction consisting of a single proton-neutron collision. Assuming this mechanism, an average kinetic energy of approximately 19 MeV can be deduced for the struck neutron (before the collision) in the C^{12} nucleus.

I. INTRODUCTION

THE usual theoretical approach to high-energy nuclear reactions rests on considerations of nucleon-nucleon collisions inside nuclei.[1,2] Calculations of most experimental observables involve the consideration of a complex spectrum of various kinds of collisions. One of the most direct studies of these collisions is the observation of products of the so-called simple reactions, (p,pn), $(p,2p)$, $(p,p\pi^+)$, etc. These reactions involve only a small number of collisions, and result in residual nuclei with small energies of excitation. Therefore the complexities of the interactions are minimized. These simple reactions are, however, sensitive to the individual properties of the target nuclei. Nuclear shell structure, for example, appears to have a significant effect on cross sections for (p,pn) reactions.[3]

At present, the experimental information concerning simple reactions consists mainly of excitation-function measurements for (p,pn) reactions. A few studies of $(p,2p)$ and $(p,p\pi^-)$ reactions have been made. In order to gain a more detailed picture of the kinematics of these reactions, measurements of angular and energy distributions are needed. It is very difficult to obtain velocity measurements for protons and neutrons ejected in these simple reactions, because of the occurrence of many reactions that are more complex. However, radiochemical techniques are suitable for observations of the recoil properties of the heavy residual nuclei.

Many different kinds of recoil measurements can be made—each having its own particular experimental

† Work done under the auspices of the U. S. Atomic Energy Commission.

[1] R. Serber, Phys. Rev. **72**, 1114 (1947).

[2] N. Metropolis, R. Bivins, M. Storm, Anthony Turkevich, J. M. Miller, and G. Friedlander, Phys. Rev. **110**, 185 (1958). See these papers for other references.

[3] P. A. Benioff, Phys. Rev. **119**, 324 (1960). See this paper for other references.