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Collective Effects in Radiative Capture Reactions and in Nuclear Spectroscopy

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Patrick J. Daly, Principal Investigator

Progress Report for the period January 1967 to September 1967

A.E.C. Contract AT(11-1)-1672

Department of Chemistry

Purdue University
Lafayette, Indiana

September 1967

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Table of Contents

I.	Research Activities	Page 1
1.	Radiative Capture in Heavy Nuclei.	Page 1
2.	Nuclear Spectroscopy in the Re-Os-Ir Region.	Page 6
(a)	Decay Modes of Osmium and Rhenium Nuclides.	Page 6
(b)	The $A \approx 180$ Decay Chain.	Page 6
(c)	Levels of Re^{181} Populated in the Decay of New Isomers of Os^{181} .	Page 9
(d)	The Decay of Ir^{195} and $\text{Ir}^{195\text{m}}$.	Page 12
(e)	The Decay of Re^{181} .	Page 14
(f)	Levels of Os^{184} populated in Ir^{184} Decay.	Page 15
3.	Spallation Reactions Induced by He^3 and He^4 Ions.	Page 17
4.	Levels of Gd^{151} Populated in Tb^{151} Decay.	Page 19
II.	Instrumentation	Page 22
III.	Personnel	Page 23
IV.	Publications and Talks	Page 24

I. RESEARCH ACTIVITIES

The research performed during this contract period follows the lines set out in our original research proposal. It was possible to start some of our investigations in the interval between the submission of the proposal and the start of the contract period. However, as in many cases the investigations were continuous and interconnected, no attempt is made in this report to draw a sharp line between work performed before and after January 1, 1967.

1. Radiative Capture in Heavy Nuclei

(R.V. Carlson and P.J. Daly)

Analysis of the existing data on radiative capture of intermediate energy nucleons in heavy nuclei had indicated ^(1,2,3) that direct or collective modes of capture not involving compound nucleus formation make important contributions to the observed cross-sections. It had not been established whether similar mechanisms also operate in capture of composite projectiles. One of the main points of interest is that either direct or collective electric dipole capture is forbidden for composite incident particles having $N=Z$ (such as alpha particles or deuterons). The basic physical reason for this forbiddenness is that with $N=Z$ for the projectile and $N \neq Z$ for the heavy target nucleus, the dipole requirement of separation of centre of charge with respect to centre of mass cannot be achieved.

In this work, we have extended the (α, γ) experimental data by measuring cross sections for radiative capture of 5-42 MeV α -particles in In^{115} and I^{127} .

In order to test whether the projectile neutron/proton ratio does indeed have a marked effect on the probability of radiative capture, we have also measured excitation functions for capture of 3-33 MeV He^3 ions in K^{41} , Sc^{45} and Ga^{71} .

In all cases radiochemical separations and induced activity measurements were performed. The resulting (α, γ) excitation functions are closely similar rising to maxima of 150 to 170 μb at about 17 MeV bombarding energy and falling to less than 10 μb above 30 MeV. At bombarding energies above the classical Coulomb barriers, the (He^3, γ) cross-sections were found to be essentially constant at about 20 μb for $\text{K}^{41}(\text{He}^3, \gamma)$, 15 μb for $\text{Sc}^{45}(\text{He}^3, \gamma)$ and 25 μb for $\text{Ga}^{71}(\text{He}^3, \gamma)$. To exemplify the experimental data obtained, Figs 1 and 2 show the excitation functions for two of the reactions studied.

These results, together with all other existing cross section data for radiative capture in heavy nuclei of 5-50 MeV nucleons and composite projectiles, have been analysed for evidence of the reaction mechanisms involved. Almost all the (α, γ) and (d, γ) results were shown to be in reasonable agreement with statistical theory predictions, especially when corrections for multiple γ -ray cascades and angular momentum effects were included. In particular, the variation of over two orders of magnitude in the reported (α, γ) maximum cross-sections was correctly predicted by statistical theory. To allow for the different nuclear penetrabilities of the various projectiles, each of the experimental capture cross-section values was divided by the appropriate optical model total reaction cross-section. The results (Fig 3) provide strong support for the proposal that nucleon capture proceeds predominantly by direct or collective reaction mechanisms. It is also evident that non-statistical processes make important contributions in the case of He^3 ion capture.

Two papers based on this work have been accepted for publication in Nuclear Physics.

Fig 1. The experimental excitation function for the reaction $Sc^{45}(He^3, \gamma)V^{48}$

Fig 2. The experimental excitation function for the reaction $\text{I}^{127}(\alpha, \gamma)\text{Cs}^{131}$

Fig 3. Capture cross-sections (σ_c) divided by optical model total reaction cross-sections (σ_R) for known cases of radiative capture of nucleons and helium ions. The shaded areas represent the ranges of values observed for the various target nuclei studied.

2. Nuclear Spectroscopy in the Re, Os, Ir region

2(a) Decay Modes of Neutron Deficient Osmium and Rhenium Nuclides

(K.J. Hofstetter and P.J. Daly)

By studying the osmium and rhenium activities produced in proton and helium-ion bombardments of tantalum and tungsten targets, the half lives and principal radiations of Re^{179} , Re^{180} , Os^{180} and Os^{181} were established. The 20h isomer previously assigned to Re^{180} was shown to be non-existent and the new isotopes 21.5 min Os^{180} , 105min Os^{181} and 2.9 min Os^{181m} were discovered. The results are summarized in Fig 4 which shows the relevant portion of the nuclidic chart before and after our work was performed.

These results have been published.

2(b) The A=180 Decay Chain (Hofstetter and Daly)

A novel method for rapid milking of short lived Rhenium daughter activities was developed and used to confirm the genetic relationship between 21.5 min Os^{180} and 2.4 min Re^{180} . No radiations other than K x-rays were detected in Os^{180} decay and it was concluded that this isotope decays by electron capture with a log ft value in the range 4.7 ± 0.3 . The radiations occurring in Re^{180} decay were accurately measured and γ - γ coincidence measurements were also performed. A Re^{180} decay scheme consistent with all the observations was proposed (Fig 5): its most interesting and unusual feature is the two-quasi-particle state $p\ 9/2^- [514] - p\ 5/2^+ [402]$ which occurs at 1006 keV in W^{180} and de-excites almost exclusively to the first excited state. The disintegration energy of Re^{180} was determined to be 3.78 ± 0.04 MeV

	Os 181 23m	Os 182 22h	Os 183 ^{9/4} 10h	Os 184 0.018	Os 185 ^{1/4} 94d	Os 186 1.59
	€ γ.167,174	€ γ.51,16,029- .37(0.02-1.4)	€ γ.11,103, 07	€ γ.38,11, 15-144	€ γ.65,88,87, .072-75	€ 183.9526
3	Re 179 18m	Re 180 2.4m	Re 181 20h	Re 182 13h	Re 183 ^{5/4} 70d	Re 184 22.2d
	€ γ.28	€ γ.88, 106	€ γ.020-1.54	€ γ.12, 066-199	€ γ.041-41	€ γ.04,16, 170d
7	W 178 22d	W 179 5m	W 180 30m	W 181 ^{9/4} 130d	W 182 26.41	W 183 ^{1/4} 5.3s
	€ γ.113,208,1058, 072-95	€ γ.093, 135	€ γ.031	€ γ.15,14	€ σ(1.5+20)	€ γ.16,21
5	Ta 177 2.3d	Ta 178 9.4m	Ta 179 2.2h	Ta 180 8.1h	Ta 181 ^{7/4} 0.0123	Ta 182 16m
	€ γ.113,208,1058, 072-95	€ γ.88, 135	€ γ.332, 109-43	€ γ.60,71, 0930, 102	€ γ.07+ 21	€ γ.15-32, 10,112, 22,119

Os 180 22m	Os 181 2.9m	Os 182 105m	Os 183 ^{9/4} 10h	Os 184 0.018	Os 185 ^{1/4} 94d	Os 186 1.59
€	€ γ.12,14	€ γ.117,142	€ γ.51,16,028- .37(0.02-1.4)	€ γ.11,103, 07	€ γ.38,11, 15-144	€ γ.65,88,87, .072-75
Re 179 19.7m	Re 180 2.4m	Re 181 19h	Re 182 13h	Re 183 ^{5/4} 70d	Re 184 22.2d	Re 185 ^{1/4} 37.07
€ γ.29,43,42,...	€ γ.88, 104	€ γ.020-1.54	€ γ.12, 066-199	€ γ.041-41	€ γ.04,16, 170d	€ γ.04,16, 170d
W 178 22d	W 179 5m	W 180 30m	W 181 ^{9/4} 130d	W 182 26.41	W 183 ^{1/4} 5.3s	W 184 30.64
€ γ.113,208,1058, 072-95	€ γ.093, 135	€ γ.031	€ γ.15,14	€ σ(1.5+20)	€ γ.16,21	€ σ(1.01+2.1)
Ta 177 56.4h	Ta 178 9.4m	Ta 179 2.2h	Ta 180 8.1h	Ta 181 ^{7/4} 0.0123	Ta 182 16m	Ta 183 ^{1/4} 5.0d
€ γ.113,208,1058, 072-95	€ γ.88, 135	€ γ.332, 109-43	€ γ.60,71, 0930, 102	€ γ.07+ 21	€ γ.15-32, 10,112, 22,119	€ γ.046,108,053, 246,041-41

Fig 4. The Chart of the Nuclides before (above) and after (below) our investigations

Fig 5. The proposed $A=180$ decay scheme

These results have been published.

2(c) Levels of Re^{181} Populated in the Decay of the Os^{181} Isomers

(Hofstetter and Daly)

We have assigned both the 2.9 min and 105 min osmium activities produced in 30 MeV He^3 ion bombardments of W^{182} to the decay of Os^{181} . In the case of the 105 min activity, the mass assignment was based on measurements of the growth of the 365.5 keV γ -ray activity of Re^{181} . The 2.9 min activity was identified with Os^{181} by a cross bombardment technique. As in the isotone W^{179} , the Os^{181} isomers are almost certainly associated with the Nilsson states $n7/2^- [514]$ and $n 1/2^- [510]$.

Work on identification of the Re^{181} levels populated in the decay of the Os^{181} isomers is in an advanced stage. The energies and relative intensities of the γ -rays occurring in the decay of the isomers are given in Table 1. Gamma - gamma coincidence measurements have been carried out using a Ge (Li) - NaI (Tl) system and the Re^{181} level scheme shown in Fig 6 has been firmly established. In this scheme all the strong γ -rays and most of the weak ones are accommodated. A well developed rotational band based on the $p 5/2^+ [402]$ ground state has the parameters

$$E_0 = -132.5 \text{ keV}, A = + 14.22 \text{ keV}, B = +0.1078 \text{ keV}.$$

It is not yet possible to assign certain values of spin - parity to the other levels, although the 263.3 keV level almost certainly corresponds to the Nilsson $9/2^- [514]$ intrinsic state which can be populated in β^- decay by an

Table 1.

The Energies and Relative Intensities of γ -rays Observed in the

Decay of Os^{181}

Os^{181} 105 min γ -ray intensities[†]

E_{γ} (keV)	Relative Intensity	E_{γ} (keV)	Relative Intensity
K x-ray	356	758.7	11
94.1	1	788.0	24
118.3	75	797 $\pm$ 1	5
145.0	9	827.4	100
157.9	2	832.1	37
167.5	21	921.5	1
195.3	1	955 $\pm$ 1	8
228.6	5	1060.8	10
238.7	247	1077.9	3
262.5	4	1305 $\pm$ 1	4
356.3	4	1345 $\pm$ 1	1
393.8	5	1472 $\pm$ 1	3
433.8	10	1591 $\pm$ 1	1

Os^{181} 2.9 min γ -ray Intensities^{*}

E_{γ} (keV)	Relative Intensity
118.3	23
145.0	100
262.5	1

[†]Normalized to an intensity of 100 for the 827.4 keV γ -ray.

^{*}Normalized to an intensity of 100 for the 145.0 keV γ -ray.

Fig 6. Level scheme of Re^{181} from studies of the decay of the Os^{181} isomers

allowed unhindered transition. It is hoped to conclude this work in the near future by measuring conversion coefficients for some of the strongest γ -transitions.

2(d) The Decay of Ir^{195} and Ir^{195m}

(Hofstetter, Daly; investigations to be concluded by Blomberg)

By studying the iridium activities produced in α -particle bombardments of enriched Os^{192} (98.7%), the 4.2h activity previously assigned (4) to Ir^{195} decay has been identified as that of Rb^{81} , arising from reactions induced in bromine impurities in the target material. The energies and relative intensities of γ -rays which truly occur in the decay of Ir^{195} are listed in Table 2. The 98.7 and 129.6 keV γ -rays, which clearly occurred in the de-excitation of the first excited ($J^\pi = \frac{3}{2}^-$) and second excited ($J^\pi = \frac{5}{2}^-$) states of Pt^{195} , were observed to follow a 2.8 ± 0.1 h half-life; it was inferred that this half-life is associated with the β -decay of the $\text{Ir}^{195} \frac{3}{2}^+$ ground state. All the other γ -rays listed in Table 2 decayed with a 4.0 ± 0.15 h half-life.

In a series of bombardments it was shown that the 2.8h and 4.0h activities were both produced by the same nuclear reaction viz. (α, p) on Os^{192} , and that in the β -decay of Ir^{195} the $\frac{13}{2}^+$ isomeric state in Pt^{194} at 259 keV is populated to a considerable extent. It was concluded that the 4.0h decay period is associated with the decay of a high spin isomer Ir^{195m} . As in the analogous nuclides Ir^{191} and Ir^{193} , the spin-parity of the new isomer is probably $\frac{11}{2}^-$. A report of this portion of the investigation has been submitted to Nuclear Physics for publication.

Table 2.

The Energies and Relative Intensities of γ -rays Assigned to ^{195}Ir Decay. The γ -ray Energies given in Ref⁽⁵⁾ are shown for comparison.

E_{γ} (keV)	Relative Intensity	E_{γ} (keV)- Ref ⁽⁵⁾
98.7 ± 0.3	100	100
119.5 ± 0.4	3	
129.6 ± 0.4	14	130
140.2 ± 0.5	6	
172.7 ± 0.5	42	
201.1 ± 0.5	10	
211.2 ± 0.5	26	
239.8 ± 0.5	13	
252.0 ± 0.5	12	
287.3 ± 1.0	8	
290.4 ± 1.0	14	
307.0 ± 0.7	10	
319.3 ± 0.5	62	330
359.0 ± 0.5	26	
365.1 ± 0.5	50	370
409.0 ± 0.7	5	
433.0 ± 0.5	65	430
480.7 ± 0.7	15	
685.2 ± 0.5	76	660
799.8 ± 0.7	7	

Further work is planned in which the high spin levels of Pt^{195} populated in the decay of $\text{Ir}^{195\text{m}}$ will be located and characterized by coincidence measurements. The results should be particularly interesting as the known low energy spectrum of Pt^{195} levels has been the subject of much theoretical work⁽⁶⁾ based on the core-coupling model.

2(e) The Decay of Re^{181} (Blomberg and Daly)

An investigation of the decay of 20-hr Re^{181} is under way. Sources are produced by the $\text{Ta}^{181}(\text{He}^3, 3n)$ reaction, and chemical separation is performed. Table 3 lists the energies and relative intensities of the Re^{181} γ -rays found. It is hoped to combine these results with γ - γ coincidence measurements and conversion electron data⁽⁷⁾ to establish the level scheme of W^{181} .

Table 3

Energies (keV) and Relative Intensities of Re^{181} γ -rays.

Energy	Intensity	Energy	Intensity	Energy	Intensity	Energy	Intensity
93.7	.3	318.6	1.9	639.0	11.5	953.7	6.3
102.7	2.4	331.9	2.3	651.2	2.3	989.4	2.4
103.1							
109.9	5.1	360.7	30.3	661.8	4.6	1000.2	6.5
144.3	.6	365.5	100.0	693.9	.2	1009.3	4.8
		382.3	.1	738.1	.7	1075.6	1.7
164.6	.4						
165.8		398.0	1.3	803.6	7.5	1086.9	.9
				805.2			
175.2	3.1	441.8	2.7			1103.5	1.1
177.4				822.6	.2		
		475.6	2.1			1384	.3
195.0	1.1			840.4	.7		
197.0		487.2	2.8			1441	4.0
		489.0		854.5	.4		
252.2	1.3					1469	1.6
276.2	1.0	577.7	3.6	880.0	1.1		
						1538	.4
		587.6	1.1	907.5	1.9		

2(f) Levels of Os^{184} Populated in the Decay of Ir^{184}

(Le Boeuf and Daly)

The energy levels of Os^{184} have been extensively studied by reaction spectroscopists^(8,9); the ground state rotational band has been established up to high spin values but there has been definite disagreement about the location of the $K = 2$ γ -vibrational band. The even-even osmium nuclides are a favorite proving ground in attempts to develop the various vibration-rotation coupling models and Os^{184} is a particularly interesting case for which the effective moment of inertia appears to reach a maximum.

We have carried out the first detailed examination of the levels of Os^{184} populated in the decay of Ir^{184} . The activity was produced by the reaction $\text{Re}^{185}(\text{He}^3, 4n)\text{Ir}^{184}$ and chemical purification was performed. The energies and relative intensities of about 40 new Ir^{184} γ -rays were determined and extensive γ - γ coincidence data were obtained using a $\text{Ge}(\text{Li})$ - $\text{NaI}(\text{Tl})$ system. The ground state band and the γ -vibrational band shown in Fig 7 were firmly established by these measurements. Additional Os^{184} levels exist at 1446, 1621, 1836 and 2447 keV. All the strong γ -rays and most of the weak γ -rays are accommodated in the resulting level scheme.

The location of the γ -vibrational band as determined in this work is in disagreement with previous determinations^(8,10); however, the γ - γ coincidence results leave no doubt about the correctness of our interpretation. Also some unpublished results of Yamasaki et al⁽¹¹⁾ support our conclusions. From the population of high spin levels observed it can be inferred that the ground state spin of Ir^{184} is greater than the value 3^+ predicted by the Nilsson Model and the Gallagher-Moszkowski rules. This is not too surprising as similar anomalies have previously been noted for other even-A Ir isotopes, but it under-

Fig 7. The ground state rotation and γ -vibrational bands of Os^{184}

lines the need for a nuclear model which will adequately represent the behavior of nuclei in the transition region.

The experimental part of this investigation has been concluded. The results are currently being analysed and interpreted prior to their publication.

3. Spallation Reactions Induced by He^3 and He^4 Ions

(Scott and Daly)

Excitation functions for the following reactions have been determined: $\text{Ta}^{181}(\text{He}^4, \text{xn})\text{Re}^{185-\text{x}}$; $\text{Ta}^{181}(\text{He}^3, \text{xn})\text{Re}^{184-\text{x}}$; $\text{Pb}^{207}(\text{He}^3, \text{xn})\text{Po}^{210-\text{x}}$; $\text{Pb}^{208}(\text{He}^3, \text{xn})\text{Po}^{211-\text{x}}$ (where x has the values one through four) with the exceptions of the $\text{Pb}^{207}(\text{He}^3, \text{n})\text{Po}^{209}$ and $\text{Pb}^{208}(\text{He}^3, 2\text{n})\text{Po}^{209}$ reactions. The results of the experiments on Ta^{181} are typical and are shown in Fig 8.

The most striking feature of Fig 8 is the large difference in position and magnitude between the (He^3, n) , $(\text{He}^3, 2\text{n})$ curves and those for the corresponding α -induced reactions. This discrepancy can be largely accounted for on the basis of threshold effects and the large difference in binding energies of He^3 and He^4 nuclei. Using He^3 ions as the incident particles, it is impossible to obtain excitation energies in the region in which the (He^3, n) and $(\text{He}^3, 2\text{n})$ excitation functions are expected to reach their maximum values.

It is also apparent (Fig 8) that the sum of the (He^3, xn) curves is considerably less than that of the (He^4, xn) curves. To determine if charged-particle emission is important in He^3 -induced reactions in this mass region, one or more points on the excitation functions for the following reactions were determined: $\text{W}^{186}(\text{He}^3, \text{p})\text{Re}^{188}$; $\text{Bi}^{209}(\text{He}^3, \text{pn})\text{Po}^{210}$; $\text{W}^{186}(\text{He}^3, \text{p}2\text{n})\text{Re}^{188}$; $\text{Ta}^{181}(\text{He}^3, 2\text{p})\text{Ta}^{182}$; $\text{Ta}^{181}(\text{He}^3, \alpha)\text{Ta}^{180}$; $\text{Ta}^{181}(\text{He}^3, \alpha 2\text{n})\text{Ta}^{178}$. Inclusion of these results still does not produce agreement between the two total reaction cross sections.

Fig 8. Excitation functions for (He^3, xn) and (α, xn) reactions in Ta^{181}

Theoretical optical model calculations will be carried out to fit the experimental total reaction cross sections. By using Monte Carlo techniques to reproduce the excitation functions, it is expected that more information concerning the mechanism of He^3 -induced reactions will be obtained.

4. Levels of Gd^{151} Populated in Tb^{151} Decay (Bansal and Daly)

The electron capture decay of Tb^{151} was investigated using $\text{Ge}(\text{Li})$ and $\text{NaI}(\text{Tl})$ detectors in singles and coincidence measurements. Separate bombardments of enriched Eu^{151} with 33 MeV He^3 ions and with 35 MeV α -particles were used to distinguish γ -rays of 18 h Tb^{151} from those of 18.5 h Tb^{152} . The energies and relative intensities of about sixty Tb^{151} γ -rays ranging from 108.1 to 2395 keV were measured. These measurements were combined with published conversion electron data to estimate conversion coefficients for many of the lower energy transitions. Extensive $\text{Ge}(\text{Li})$ - $\text{NaI}(\text{Tl})$ γ - γ coincidence measurements were carried out and the results are summarized in Table 4.

A rather complete Gd^{151} level scheme has been constructed (Fig 9), in which most of the observed γ transitions are accommodated. This scheme is in disagreement with many features of the Gd^{151} level scheme shown in the Nuclear Data Sheets. Work is continuing on assigning spin and parities to the levels and on interpreting the results in terms of nuclear models.

Fig 9. Levels of Gd^{151} populated in β -decay of Tb^{151}

E_γ (keV)	108.1	180.1	192.2	252.2	287.2	380.7	395.8	416.2	426.8	443.8	467.8	478.9	510.8	586.8	603.8	615.8
108.1		Y	Y	Y	Y	Y	N	Y	N	Y		Y	N	N		Y
180.1	Y				Y	N	Y		Y	N	N	N		N	N	Y
192.2	Y			Y												
252.2	Y	N	Y			N	N		Y	N		Y		Y	N	N
287.2	Y	Y	N	Y		Y	N	Y		Y		N		N		Y
380.7																
395.8	N	Y				Y		Y	Y					N		Y
416.2																
426.8																
443.8	Y				Y	Y	^w Y			N		N		N		N
467.8																
478.9	Y	N		Y	N	N	^w Y		Y					N	Y	N
510.8	Y		Y													
586.8	N	N	N	Y	^w Y	N	^w Y	N	Y	N		^w Y			Y	N
603.8							Y							Y		
615.8	Y	N	N	N	Y	Y	N	^w Y	Y	N		N	Y			

Table 4. Gamma-gamma coincidence results for Tb^{151} decay. Y represents an observed coincidence relationship and N the absence of a coincidence relationship. A case in which the coincidence fraction is small is indicated by a superscript w.

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II. INSTRUMENTATION

The electronics group has provided maintenance and service during the present contract period. In this period our new counting room was completed and all counting instruments were set up therein.

A new lithium-drifted germanium spectrometer was installed and a new Ge(Li) - NaI(Tl) coincidence spectrometer, incorporating the Packard 45 two parameter analyser, was set up and was heavily used. Data are punched on to paper tape and are then processed on a IBM 7094 computer using programs written by members of this group.

A vacuum cryostat system has been constructed which will be used with a lithium-drifted silicon detector to measure conversion electron energies and conversion coefficients.

III PERSONNEL

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B. Long, Electronics Technician
L. Eckstein, Draftsman and Driver

* Resigned, September 1967

IV. PUBLICATIONS AND TALKS

- Decay Properties of Neutron Deficient Osmium and Rhenium Isotopes. I. Decay Modes of Re^{179} , Re^{180} , Os^{180} and Os^{181} . K. J. Hofstetter and P. J. Daly, Phys. Rev. 152, 1050 (1966).
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