THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 165, NO. 4 — 20 JANUARY 1968

Mean Lives of Some States in B^{10}†

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(Received 27 July 1967)

Doppler shifts of γ rays from some excited states of B^{10} nuclei produced in the reaction $B^{11}(He^3,\alpha)B^{10}$ have been measured with Ge(Li) and NaI(Tl) detectors. From these Doppler shifts the following information concerning mean lives of states in B^{10} has been deduced: $\tau(1.74\text{ MeV})\leq 4\times 10^{-14}$ sec, $\tau(2.15\text{ MeV})=(2.1_{-0.5}^{+0.8})\times 10^{-12}$ sec, and $\tau(3.59\text{ MeV})=(1.7\pm 0.7)\times 10^{-13}$ sec.

I. INTRODUCTION

TRANSITION rates among low excited states of the nucleus B^{10} have recently been the subject of considerable speculation. Doppler-shift attenuation measurements made in three laboratories[1-4] have yielded values for mean lives of states at 1.74, 2.15, and 3.59 MeV. Cohen and Kurath[5] performed a shell-model calculation from which they deduced transition probabilities for all of the $M1$ transitions from these levels. Perhaps the most definite conclusion to be drawn from a comparison of experimental results for B^{10} and the calculations of Cohen and Kurath is that the value of the mean life of the 1.74-MeV state measured in this laboratory[1] disagrees with the calculated result by about a factor of 35. In addition, Fisher *et al.*[3] have presented a measurement which indicates that the mean life of the 1.74-MeV state in B^{10} is too short to be measured by the Doppler-shift attenuation method.

For these reasons, we have remeasured the Doppler shift of γ rays from the 1.74-MeV state in B^{10} with improved equipment and techniques. At the same time, we have made a new and more accurate determination of the mean life of the 2.15-MeV state in B^{10}. These measurements are described below. Also presented is a description of the measurement of the mean life of the 3.59-MeV state in B^{10}. Results of this latter measurement have been presented briefly before.[2]

† Supported in part by the U. S. Atomic Energy Commission.
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[1] J. A. Lonergan and D. J. Donahue, Phys. Rev. 139, B1149 (1965); 145, 998(E) (1966).
[2] J. A. Lonergan and D. J. Donahue, Bull. Am. Phys. Soc. 11, 27 (1966).
[3] T. R. Fisher, S. S. Hannah, and P. Paul, Phys. Rev. Letters 16, 850 (1966).
[4] E. K. Warburton, J. W. Olness, K. W. Jones, C. Chasman, R. A. Ristinen, and D. H. Wilkinson, Phys. Rev. 148, 1072 (1966).
[5] S. Cohen and D. Kurath, Nucl. Phys. 73, 1 (1965).

II. METHOD

Since the Doppler-shift attenuation method has been described many times, only those aspects of it which are pertinent to the present experiments are given here. Nuclei in excited states produced with a speed v_i in a nuclear reaction pass through a slowing down medium (usually the target backing) until, at the time they decay, they are moving with an average speed

$$\langle v\rangle=\frac{1}{\tau}\int_0^\infty v(t)e^{-t/\tau}dt,\qquad(1)$$

where τ is the mean life of the excited state. The distribution in time of the velocities of recoiling nuclei $v(t)$ can be determined from the slowing down properties of the target backing and the initial speed v_i. Thus, if $\langle v\rangle$ is measured, and v_i is either measured or calculated, the mean life of the nuclear state can be obtained from Eq. (1), and the slowing down properties of the medium through which the ions move.

In the experiments described here we have divided the range of recoil velocities into two parts. In the first region, $v'\leq v\leq v_i$, the stopping power of the target backing is assumed to be a constant, so that

$$\frac{dE}{dx}=-m\frac{dv}{dt}=\frac{mv_i}{\beta},$$

and

$$v(t)=v_i(1-t/\beta),\quad v'\leq v\leq v_i.\qquad(2)$$

In the second region, $0 \leq v \leq v'$, the stopping power is assumed to be proportional to the velocity of the moving ion,

$$\frac{dE}{dx} = -m\frac{dv}{dt} = \frac{m}{\alpha}v,$$

so that

$$v(t) = v_1 e^{-t/\alpha}. \qquad (3)$$

Here v_1 is a constant of integration, and is chosen so that the speed v' will occur at the same time t_1 in both regions. Equation (1) can now be written as the sum of two integrals, and upon integration yields

$$\frac{\langle v\rangle}{v_i} = \left\{\left[\frac{\tau}{\beta} - \frac{v'}{v_i}\left(\frac{\tau}{\alpha+\tau}\right)\right]\exp\left[-\frac{\beta}{\tau}\left(1-\frac{v'}{v_i}\right)\right] + 1 - \frac{\tau}{\beta}\right\}, \qquad (4)$$

where, as indicated above, α, β, and v' are properties of the slowing-down medium. The validity of the approximations made to obtain Eqs. (2) and (3) is illustrated in Fig. 1. In this figure the values of stopping power for boron ions in copper, obtained from the compilation of Northcliffe,[6] are plotted as a function of the speed of the recoiling ions. The uncertainties in the stopping power, which according to Northcliffe are about 10% of the values, are indicated by the cross-hatched area, and the stopping powers given by Eqs. (2) and (3) with appropriate values of α, β, and v' are shown with solid lines. As can be seen, uncertainties in stopping powers are large enough to mask errors which might result from the assumed form of dE/dx versus v.

Recoil ion velocities encountered in this work ranged from 0.8 to 8.0×10^8 cm/sec. We have shown, using the method described by Blaugrund,[7] that for this range of velocities, the effect on our results of neglecting large-angle scattering in the slowing down process is negligible.

In the experiments described here, B^{10} nuclei in excited states were produced by the reaction $B^{11}(He,\alpha)B^{10*}$. The direction of recoil of B^{10*} nuclei was fixed by observing α particles with a silicon surface-barrier detector located at 90° to the incident He^3 beam. γ rays were detected in time coincidence with these α particles, and the difference in energy of those γ rays emitted at approximately 0° and 180° to the recoiling B^{10} nuclei was measured either with a lithium-drifted-germanium or a NaI(Tl) detector. The ratio of this energy difference to the unattenuated difference which would be obtained if the recoiling nuclei emitted γ rays while moving with a speed v_i is written

$$\frac{\Delta\bar{E}}{\Delta\bar{E}_i} = \frac{\langle\langle v\rangle\langle\cos\varphi_0\rangle_\gamma\rangle_v - \langle\langle v\rangle\langle\cos\varphi_\pi\rangle_\gamma\rangle_v}{\langle v_i\langle\cos\varphi_0\rangle_\gamma\rangle_v - \langle v_i\langle\cos\varphi_\pi\rangle_\gamma\rangle_v}, \qquad (5)$$

where $\langle\cos\varphi\rangle_\gamma$ is the value of the cosine of the angle between a direction of a recoiling nucleus and the direction of motion of detected γ rays averaged over the dimensions of the γ-ray detector, and $\langle v\langle\cos\varphi\rangle_\gamma\rangle_v$ is averaged over all possible directions of v as defined by the finite dimensions of the α-particle detector. As mentioned above, the numerator of this expression is measured and the denominator can either be calculated or it can be measured by using a thin, self-supported target.

Finally, to use measured results with Eq. (1) to obtain mean lives, we assume

$$F = \Delta\bar{E}/\Delta\bar{E}_i = \langle v\rangle/v_i, \qquad (6)$$

that is, we assume that the *ratio* of Doppler shifts obtained with finite solid angles for both the particle and γ-ray detectors is the same as that which would result if point detectors were used.

III. RESULTS

A. 1.74-MeV Level

Figure 2 shows an α-particle spectrum obtained with the silicon detector at 90° to the incident 2-MeV He^3 beam. As can be seen, α particles to the 2.15- and 1.74-MeV levels are not well resolved. No matter how carefully a window is set over the 1.74 MeV state, one must worry about whether or not some α particles leaving B^{10} in the 2.15-MeV level get into the window and trigger the coincidence circuit. Since the mean life of the 2.15-

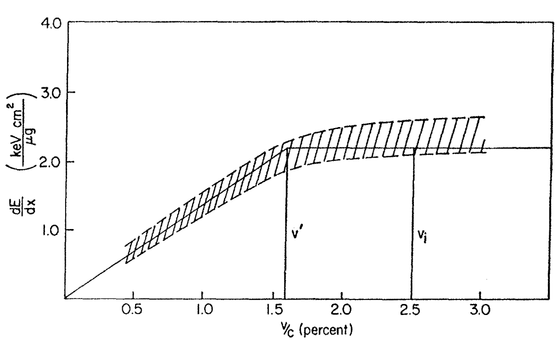

FIG. 1. Stopping power versus velocity. Range of values from Ref. 6 are shown by cross-hatched area. Approximations used in present work are indicated by straight lines.

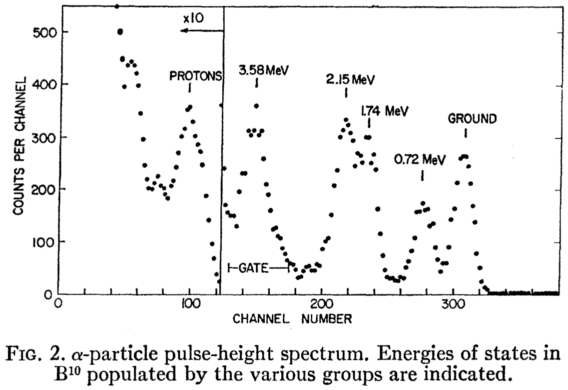

FIG. 2. α-particle pulse-height spectrum. Energies of states in B^{10} populated by the various groups are indicated.

[6] L. C. Northcliffe, Ann. Rev. Nucl. Sci. 13, 67 (1963).
[7] A. E. Blaugrund, Nucl. Phys. 88, 501 (1966).

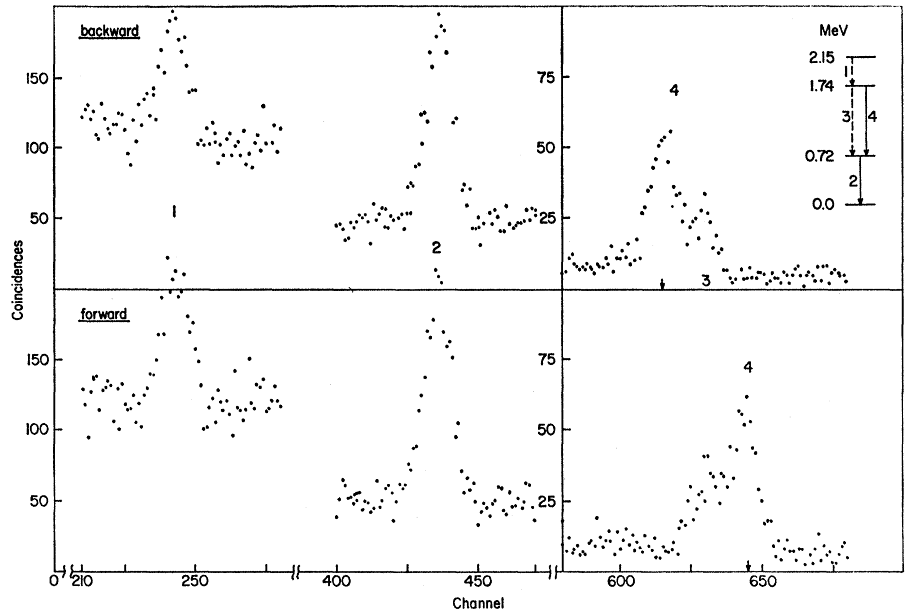

FIG. 3. Pulse-height spectrum of γ rays in coincidence with α particles to the 1.74- and 2.15-MeV states in B^{10}. Upper and lower curves were obtained with Ge(Li) detector at about 180° and 0° to the direction of recoiling B^{10} ions, respectively.

MeV state is much longer than that of the 1.74-MeV state, the average Doppler shift of γ rays emitted from the 1.74-MeV state could be seriously influenced if some of these γ rays were part of a cascade from the 2.15-MeV state. As will be mentioned below, this is evidently what happened in our earlier measurement. In the present experiment this difficulty was circumvented by placing the window over all α particles leading to both the 2.15- and 1.74-MeV states. The 1.02-MeV γ rays emitted in coincidence with those α particles can then come from the 1.74-MeV states populated either directly in the (He^3,α) reaction or by cascades from the 2.15-MeV state. γ rays produced by the two routes have different Doppler shifts, and, in fact, when detected with a 30-cm^3 Ge(Li) crystal, could be resolved. Thus, even though no attempt was made to resolve α particles to the two states in question, we were able to measure the Doppler shift of γ rays emitted only from those 1.74-MeV states populated directly by the (He^3,α) reaction.

Spectra of γ rays in coincidence with α particles to the 1.74- and 2.15-MeV states in B^{10}, obtained with the Ge(Li) crystal located at 0° and 180° to the direction of motion of the recoiling B^{10} nuclei, are shown in Fig. 3, together with a partial energy level scheme of B^{10} which indicates the observed transitions. To obtain each of the spectra illustrated, a 50-$\mu g/cm^2$ foil evaporated on a thick copper backing was bombarded with about 10^{-2} C of 2-MeV He^3 ions. A total of five such spectra were taken in each direction, and the centroid of peak (4) was computed for each run. From these centroids, a mean value of the $\Delta\bar{E}$ was deduced for γ rays in transition (4).

The γ-ray peak produced by the decay of the long-lived 0.72-MeV state is not Doppler-shifted, and provides a very convenient energy calibration and check on the stability of the system. Including measurements at both 0° and 180° to the recoiling B^{10}, extending over a period of several days, a total of ten determinations of the centroid of this peak was made. A statistical analysis of these data showed that the standard deviation of a single measurement from the mean was 0.65 keV, about 4% of the width at half-maximum of the peak.

Unattenuated Doppler shifts for the 1.74- to 0.72-MeV transition were calculated from the geometrical arrangement of the experiment. To ensure that nothing was overlooked in these calculations, the difference in energy between γ rays emitted in forward and backward directions was also measured, using a self-supported 50-$\mu g/cm^2$ B^{11} target. The spectra obtained from these measurements were similar to those shown in Fig. 3, but transitions 1, 2, and 3 all showed large energy shifts in going from front to back directions, and transitions 3 and 4 appeared as a single line. The results of all of those measurements as well as calculated full shift $\Delta\bar{E}_i$ are shown in Table I. The errors shown in the table are a

TABLE I. $\Delta\bar{E}=\bar{E}_f-\bar{E}_b$; 1.74 → 0.72 MeV transition.

	Copper-backed	Self-supported	Calc. full shift
	46.3 keV	48.5 keV	
	46.8	47.7	
	47.6	47.7	
	46.6	46.7	
	46.8		
Average	46.8±0.7 keV	47.7±0.7 keV	49.6±1 keV

$$F=\frac{\Delta\bar{E}\text{ (copper backed)}}{\frac{1}{2}[\Delta\bar{E}\text{(self-supported}+\Delta\bar{E}\text{ (calc))}]}=0.96\pm0.03$$

combination of the statistical errors in location of the centroids of the peaks and of the uncertainty in the energy calibration of the γ-ray spectrum. The error in the calculated full shift covers uncertainties in the geometry of the system. As can be seen, the value of $\Delta\bar{E}$ obtained with the self-supported foil is slightly less than the calculated maximum shift. This difference could be attributed to the slowing down of ions in the boron foil. However, within standard deviations the two values nearly overlap, and we have chosen to use their average for $\Delta\bar{E}_i$. Based on the results presented in Table I, we conclude that the ratio $\Delta\bar{E}/\Delta\bar{E}_i \geq 0.90$, where the limit has been set using two standard deviations. Using this limit in Eq. (4) together with values of $\alpha_{Cu}=2.7 \pm 0.4\times10^{-13}$ sec and $\beta_{Cu}=3.9\pm0.4\times10^{-13}$ sec, obtained from Northcliffe's stopping powers for boron ions in copper,[6] we obtain a limit to the mean life of the 1.74-MeV state in B^{10} of $\tau\leq4\times10^{-14}$ sec. This result is in good agreement with the result quoted by Fisher *et al.*[3]

In looking at our previous work, we have concluded that if we had used a current value[8] for the branching ratio of the 2.15-MeV state in B^{10} when corrections were made for cascades from that state, instead of the one actually used,[9] our former results could have been made consistent with the present work.

B. 2.15-MeV State

As mentioned previously, the spectra illustrated in Fig. 3 were obtained by counting all γ rays in coincidence with α particles to the 2.15- and 1.74-MeV states in B^{10}. Thus, the shift in energy between the forward and backward directions of the 0.41-MeV peak can be used to deduce the mean life of the 2.15-MeV state.

TABLE II. $\Delta\bar{E}=\bar{E}_f-\bar{E}_b$; 2.15 → 1.74 MeV transition.

	Backing		
	Copper	Magnesium	Calc. max.
	2.0 keV	6.4	
	2.0	4.8	
	3.8	3.2	
	1.3	7.1	
	1.7		
Average	2.2±0.8 keV	5.4±1.0 keV	20.3±1 keV

$$F_{Cu}=\frac{\text{copper backed}}{\text{calc. max.}}=0.11\pm0.04$$

$$F_{Mg}=\frac{\text{magnesium backed}}{\text{calc. max.}}=0.27\pm0.05$$

$$\tau_{Mg}=(2.1_{-0.7}^{+1.2})\times10^{-12}\text{ sec}$$

$$\tau_{Cu}=(2.0_{-0.8}^{+1.1})\times10^{-12}\text{ sec}$$

Because the mean life of this state is long, the shift measured with a copper backing was small, and to ensure that the slowing down of recoiling nuclei was treated properly, a second set of measurements was made with a target of about 50 μg/cm^2 of B^{11} evaporated on a thick magnesium backing. Results with these two backings are listed in Table II. The measured and calculated full shifts in Table I combined with these results yield mean values of $F=\langle v\rangle/v_i$ listed in Table II. To obtain the mean lives shown in the table, values of $\alpha_{Mg}=(3.3\pm0.5)\times10^{-13}$ sec and $\beta_{Mg}=(1.3\pm0.2)\times10^{-12}$ sec were used. The average of the mean lives measured for copper and magnesium backings is

$$\tau_{2.15}=\left(2.1\begin{matrix}+0.8\\-0.5\end{matrix}\right)\times10^{-12}\text{ sec.}$$

The error is approximately a standard deviation, and includes uncertainties in the Doppler-shift measurements and in the stopping powers parameters used in Eq. (4). This mean life is only in fair agreement with our previous measurement, and with that of Fisher *et al.*,[3] but because of the more refined equipment used in this work we have considerably more confidence in the present result than in our previous one.

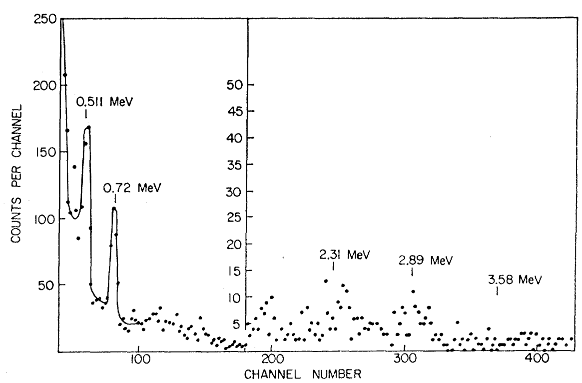

FIG. 4. Pulse-height spectrum of γ rays in coincidence with α particles to the 3.59-MeV state in B^{10}, obtained with a NaI(Tl) detector.

C. 3.59-MeV Level

To measure the mean life of the 3.59-MeV level the window on the single-channel analyzer was set over the group of α particles leading to this state, as shown in Fig. 2. γ rays with energies of 2.87 MeV, emitted in the 3.59 → 0.72 MeV transitions were detected in coincidence with α particles in this window using a 3×3 in. NaI(Tl) detector. The gain of the γ-ray detection system was stabilized electronically. Two sets of γ-ray spectra were obtained with the NaI detector located at 0° and 180° to the direction of the recoiling B^{10} nuclei. A plot of one of these spectra is shown in Fig. 4. This curve represents a total beam charge of about 10^{-2} C.

[8] T. Lauritsen and F. Ajzenberg-Selove, Nucl. Phys. **78**, 1 (1966).

[9] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).

It is apparent that the NaI results, when compared to those of the germanium crystal, leave something to be desired. However, from this curve and three others like it, we were able to obtain a value for the ratio

$$F=\Delta\bar{E}/\Delta\bar{E}_i=\langle v\rangle/v_i=0.65\pm0.1\,.$$

Copper backings were used in measurements on this level, and from the slowing-down parameters of copper listed above, and from Eq. (4), we obtain a value for the mean life of the 3.59-MeV state in B^{10} of $\tau=1.7\pm0.7\times10^{-13}$ sec. This result is in agreement with the two previous measurements.[3,4]

IV. SUMMARY

In Table III we summarize all of the measurements on mean lives of three states in B^{10}. As can be seen, all measurements now show reasonable agreement. From the mean lives for the three states shown in the table, and from the branching ratios for the 2.15-MeV and the 3.59-MeV states,[8] a total of six $M1$ transition probabilities can be obtained, and, hopefully, compared with the calculations of Cohen and Kurath.[5] However, as illustrated in the discussions of Warburton *et al.*,[4] uncertainties in the multipolarities of all but two of the transitions make such comparisons ambiguous. Of those two, the $1.74\rightarrow0.72$ MeV transition is too fast to be measured by the Doppler-shift method, a result in agreement with Cohen and Kurath's predictions. Finally, the transition probability of the $2.15\rightarrow1.74$ MeV $M1$, $\Delta T=1$, transition obtained from our measurement of the mean life and from the branching ratio of that state[8] is about one-fourth of the best value calculated for it.

TABLE III. Mean lives (seconds) of states in B^{10}.

State (MeV)	BNL[a]	Stanford[b]	Present work
1.740		$<2.8\times10^{-14}$	$<4.0\times10^{-14}$
2.154		$(4.0\pm1.0)\times10^{-12}$	$(2.1_{-0.5}^{+0.8})\times10^{-12}$
3.585	$(1.20\pm0.43)\times10^{-13}$	$(1.33\pm0.35)\times10^{-13}$	$(1.7\pm0.7)\times10^{-13}$

[a] Reference 4.
[b] Reference 3.

PHYSICAL REVIEW VOLUME 165, NUMBER 4 20 JANUARY 1968

Theory of the Photodisintegration of the Deuteron and of Other Nuclei*

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(Received 7 August 1967)

The interaction between the radiation field and a collection of nucleons is formulated in a manner suitable for the employment of the Franz-Stech classification of electromagnetic multipoles, and for separating the more certain parts of the interaction energy from the speculative ones, the uncertainties being concerned with exchange currents. The separation is effected by bringing the entrance of the electric charge density into evidence. The heuristic introduction of the intensity of magnetization as though it were due to magnetic moments of the fixed-magnetic-moment type is avoided, the whole interaction being expressed in terms of currents. Part of the general discussion neglects retardation so as to bring out the reasons for the particular grouping of terms, but retardation effects are included later on. It is shown that in a nonrelativistic theory the usual procedure of making calculations as though the center of mass of the p-n system were fixed may be justified as an approximation provided certain assumptions are made. The recoil of the center of mass caused by photon absorption is explicitly considered in this connection. Some limitations of the theory caused by relativistic effects are mentioned. The relationships of contributions to the electric-multipole transition amplitudes caused by the nucleon magnetic moments, as well as of related contributions of radial components of the Schrödinger current, are discussed in relation to the retardation effects. A brief review of the limitations of space-time models and of the accomplishments of the pure S-matrix approach to the $d(\gamma,n)p$ problem indicates the continued value of both approaches.

I. INTRODUCTION

IN connection with nuclear photodisintegration in general and especially that of the deuteron, it is desirable to employ a classification of electromagnetic multipoles making use of irreducible tensors. The suitability of such a treatment for the discussion of problems involving rotations of coordinate axes is clear. For this reason as well as the aesthetic appeal of a plan based on transformation properties, this classification has displaced other ways of dealing with electromagnetic multipole radiation. The well-known necessity of introducing exchange currents when exchange forces are present in the nuclear Hamiltonian makes it desirable, however, to formulate the interaction between the radiation field and the nucleons in a manner which separates

* Supported by the U. S. Atomic Energy Commission (Yale-1807-46), the U. S. Army Research Office-Durham, and by the Air Force Office of Scientific Research, Office of Aerospace Research, U. S. Air Force, under AFOSR Grant No. AF 394-66.

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