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FOREWORD

The Summary Report of the Physics Division of the Argonne National Laboratory is issued monthly for the information of the members of the Division and a limited number of other persons interested in the progress of the work. Each active project reports about once in 3 months, on the average. Those not reported in a particular issue are listed separately in the Table of Contents with a reference to the last issue in which each appeared.

This is merely an informal progress report. The results and data therefore must be understood to be preliminary and tentative.

The issuance of these reports is not intended to constitute publication in any sense of the word. Final results either will be submitted for publication in regular professional journals or, in special cases, will be presented in ANL Topical Reports.

TABLE OF CONTENTS

The date of the last preceding report is indicated after the title of each project below. Projects that are not reported in this issue are listed on subsequent pages.

		<u>PAGE</u>
I.	<u>EXPERIMENTAL NUCLEAR PHYSICS</u>	
I-22-18	SCATTERING OF CHARGED PARTICLES (ANL-6534, April-May 1962)	
	H. W. Broek and J. L. Yntema	1
	Groups of alpha particles whose angular distributions correspond to $\ell = 2$ are seen at excitations of about 1 MeV in all targets studied. These targets also yield groups of $\ell = 3$ alphas at about 4 MeV excitation. These groups are usually excited more strongly in even-even targets than in odd-A targets. For the targets studied, the 3^- cross section increases with A, while the 2^+ cross section shows no regular variation with A.	
I-31-1	ELASTIC SCATTERING OF PROTONS (New project)	
	L. L. Lee, Jr. and J. P. Schiffer . . .	3
	Preliminary results have been obtained on the elastic scattering of 8-MeV protons from Ca^{40} , Ni^{58} , Ni^{60} , Cu^{63} , and Cu^{65} using the tandem Van de Graaff generator.	
I-98-30	UNBOUND NUCLEAR LEVELS IN THE KEV REGION (ANL-6534, April-May 1962)	
	C. T. Hibdon	5
	Revised values of the widths of some of the unbound levels of F^{20} are given. Many peaks were observed in the 130-300 keV region but an analysis of these peaks is deferred until inelastic scattering can be taken into account.	

	<u>PAGE</u>
IV. <u>PLASMA PHYSICS</u>	
IV-10-4 MORPHOLOGY OF HIGH-FREQUENCY PLASMOIDS (ANL-6455, November- December 1961)	
A. J. Hatch	11
A photographic and visual study of the structure of high-frequency plasmoids as related to plasmoid mechanisms is described.	
V. <u>THEORETICAL PHYSICS, GENERAL</u>	
V-12-1 SENIORITY MIXING IN $1f_{7/2}$ NUCLEI (New project)	
R. D. Lawson and B. Zeidman	27
Transition strengths of neutron pickup reactions are calculated for $1f_{7/2}$ nuclei.	
PUBLICATIONS	31
PERSONNEL CHANGES IN THE ANL PHYSICS DIVISION . . .	33

PROJECTS NOT REPORTED IN THIS ISSUE

A reference to the last preceding report is given in parentheses for each project.

I. EXPERIMENTAL NUCLEAR PHYSICS

- I-2. Neutron Detectors (ANL-6534, April-May 1962), S. I. Baker, L. M. Bollinger, and G. E. Thomas.
- I-3. Cross-Section Measurements with the Fast Neutron Velocity Selector (ANL-6534, April-May 1962), L. M. Bollinger, L. M. Bogan, R. T. Carpenter, R. E. Cote', H. E. Jackson, J. P. Marion, and G. E. Thomas.
- I-7. Gamma-Ray Spectra from Capture in Neutron Resonances (ANL-6146, April-May 1960), L. M. Bollinger, R. T. Carpenter, and H. E. Jackson.
- I-10. Tandem Van de Graaff Accelerator (ANL-6262, December 1960), F. P. Mooring and J. R. Wallace.
- I-11. Installation and Operation of the Van de Graaff Generator (ANL-6488, January 1962), J. R. Wallace.
- I-14. Pulsed Beams for the Van de Graaff Machine (ANL-6391, July-August 1961), R. E. Holland and F. J. Lynch.
- I-18. Neutron Polarization and Differential Cross Sections (ANL-6517, February-March 1962), R. O. Lane and W. F. Miller.
- I-19. Nuclear Resonance Absorption of Gamma Rays (ANL-6534, April-May 1962), S. S. Hanna, G. J. Perlow, J. P. Schiffer, and J. A. Weinman.
- I-28. Angular Correlations in Charged-Particle Reactions (ANL-6358, April-May 1961), T. H. Braid.
- I-30. Calculation of Reduced Widths from Resonant Scattering of Protons by a Diffuse Potential (ANL-6534, April-May 1962), J. P. Schiffer.

- I-34. Decay of ${}_{68}\text{Er}^{172}$ (ANL-6432, September-October 1961), S. B. Burson and R. G. Helmer.
- I-35. Decay of ${}_{57}\text{La}^{135}$ (19.5 hr) (ANL-6391, July-August 1961), S. B. Burson and H. A. Grench.
- I-55. Capture Gamma-Ray Spectra for Neutrons with Energies from 0.1 to 10 eV (ANL-6052, September 1959), S. Raboy and C. C. Trail.
- I-60. 7.7-Meter Bent-Crystal Spectrometer (ANL-6517, February-March 1962), R. K. Smither.
- I-80. Molecular Beam Studies (ANL-6517, February-March 1962), W. J. Childs, J. Dalman, D. von Ehrenstein, and L. S. Goodman.
- I-102. Neutron Cross Sections by Self-Detection (ANL-6376, June 1961), J. E. Monahan and F. P. Mooring.
- I-111. Semiconductor Detectors (ANL-6455, November-December 1961), H. M. Mann and J. W. Haslett.
- I-144. Investigation of Scintillators (ANL-6517, February-March 1962), L. J. Basile and W. L. Buck.

II. MASS SPECTROSCOPY

- II-23. Sputtering Experiments in the Rutherford Collision Region (ANL-6488, January 1962), M. S. Kaminsky.
- II-28. Kinetics of Chemical Reactions in the Gas Phase (ANL-6517, February-March 1962), J. Berkowitz and S. Wexler.
- II-29. Gaseous Species in Equilibrium at High Temperatures (ANL-6455, November-December 1961), J. Berkowitz.
- II-39. Fragmentation of Cyanogen (ANL-6488, January 1962), H. E. Stanton.

- II-40. Fragmentation of Hydrocarbons (ANL-6534, April-May 1962), H. E. Stanton.
- II-41. Consecutive Ion-Molecule Reactions (ANL-6455, November-December 1961), S. Wexler and N. Jesse.

V. THEORETICAL PHYSICS, GENERAL

- V-1. The Deformation Energy of a Charged Liquid Drop (ANL-6432, September-October 1961), S. Cohen and W. J. Swiatecki.
- V-3. Dynamics of Nuclear Collective Motion (ANL-6517, February-March 1962), D. R. Inglis.
- V-4. Relative β -Decay Probabilities for ${}_{19}\text{K}^{40}$ (ANL-6455, November-December 1961), D. Kurath.
- V-8. Relationships of Collective Effects and the Shell Model (ANL-6358, April-May 1961), D. Kurath.
- V-9. Interpretation of Experiments Involving Excitation of the 15.1-MeV Level of C^{12} (ANL-6391, July-August 1961), D. Kurath.
- V-15. Statistical Properties of Nuclear Energy States (ANL-6488, January 1962), N. Rosenzweig.
- V-25. Scattering of Alpha Particles by a Vibrational Nucleus (ANL-6517, February-March 1962), L. J. Tassie.
- V-33. Flux Quantization and Time-Reversal Degeneracy (ANL-6517, February-March 1962), M. Peshkin and W. Tobocman.
- V-42. Time Reversal and Superselection (ANL-6488, January 1962), H. Ekstein.
- V-46. Elastic Nucleon-Nucleon Scattering at High Energies and Small Angles (ANL-6517, February-March 1962), K. Hiida.

I. EXPERIMENTAL NUCLEAR PHYSICSI-22-18 Scattering of Charged Particles

(51210-01)

H. W. Broek and J. L. Yntema
Reported by H. W. Broek

INELASTIC SCATTERING OF ALPHA PARTICLES BY NUCLEI
IN THE REGION FROM Fe^{54} to Zn^{68}

The elastic and inelastic scattering of 43-MeV alpha particles by nuclei in the region from Fe^{54} to Zn^{68} has been studied at the Argonne 60-in. cyclotron. Targets studied were Fe^{54} , Mn^{55} , Fe^{56} , Ni^{58} , Co^{59} , Ni^{60} , Cu^{63} , Zn^{64} , Cu^{65} , and Zn^{68} . The alpha particles were detected by silicon surface-barrier detectors. The line width was about 1.0% of the alpha energy.

The angular distributions for elastic and inelastic scattering show the familiar pattern of oscillations with a period of about 10° and an envelope (a line drawn through the successive maxima) which decreases monotonically with increasing angle. All of the targets show a group at about 1 MeV whose oscillations are out of phase with those of elastic scattering. For the even-even targets this group is due to the 2^+ first excited state, which is believed to be describable as a one-phonon oscillation. For the odd-A targets this group shows an angular distribution which is quite similar to that seen for the even-even targets. Hence, an $l = 2$ oscillation is also excited in those targets, and this oscillation couples to the spin I of the ground state to produce $2I + 1$ or $2l + 1$ levels (whichever is less). The number of known levels¹ at roughly 1 MeV is consistent with this expectation (for the odd-A targets studied) except for Mn^{55} . Mn^{55} only four levels are known in the

¹Nuclear Data Sheets, National Academy of Sciences, National Research Council, 1959 (U. S. Government Printing Office, Washington, D. C.).

1-MeV region, whereas five are required by the above interpretation. Possibly the $\frac{7}{2}^-$ first excited state at 0.126 MeV may belong to this quintet, or alternatively there may be a level which has not yet been observed.

Fig. 1. Cross sections for $l = 2$ first inelastic group at the maximum near 41° .

Figure 1 plots the intensity of the first inelastic group as a function of A . No regular variation with A is found. Also, no shell effects for protons is found since the Ni points are intermediate. A shell effect for neutrons may exist since the Fe^{54} point is the lowest of the even-even nuclei. A definite odd-even effect is seen: the points for odd- A nuclei are generally lower than those for even-even nuclei. The lowest cross section is that for Mn^{55} . This low cross section may be related to the fact that the ground-state spin of this nucleus is not what is expected from simple shell-model theory.

All of the nuclei studied show one or more strong groups at about 3 - 5 MeV excitation. The angular distributions of these groups are in phase with elastic scattering and have the appearance expected for 3^- groups. One group is seen in each of the even-even nuclei, while four groups are seen² for Cu^{63} and Cu^{65} . Since the ground-state spins of Cu^{63} and Cu^{65} are $\frac{3}{2}^-$, the four groups ($2I + 1 = 4$) are presumably

²J. Saudinos, R. Beurtey, P. Catillon, R. Chaminade, M. Crut, H. Faraggi, A. Papineau, and J. Thirion, Compt. rend. 252, 96 (1961).

the coupling of a 3^- oscillation to the ground state.

Figure 2 compares the intensity of the 3^- inelastic groups at corresponding maxima in their angular distributions. The maxima chosen for comparison are those that occur near 35° in all cases.

For the odd-A targets, contributions from all of the 3^- groups were combined. Even-even targets generally show a higher cross section for $\ell = 3$

excitation than do the odd-A targets. This effect is similar to what is observed for $\ell = 2$ excitation (Fig. 1). In addition, both even-even and odd-A targets show that the cross section for $\ell = 3$ excitation increases with A. For the $\ell = 2$ excitation no such tendency was found.

Fig. 2. Cross section for the $\ell = 3$ collective groups at the maximum near 35° .

I-31-1

Elastic Scattering of Protons

(51210-01)

L. L. Lee, Jr. and J. P. Schiffer

Angular distributions of elastically scattered protons have been measured with 8-MeV protons from the Argonne tandem Van de Graaff generator. The protons were scattered from self-supporting foils of Ca, Ni^{58} , Ni^{60} , Cu^{63} , and Cu^{65} . An 18-in. scattering chamber designed by T. H. Braid was used. The detector, a silicon surface-barrier counter, could be rotated on a remotely controllable arm with a precision of 0.1° . The beam was collimated to a diameter of 0.06 in.

Fig. 3. Elastic scattering of 8-MeV protons from Ca.

and target currents of $0.1 \mu\text{A}$ were easily obtained. Measurements were made at 4° intervals between 30° and 165° to the incident beam.

Preliminary results are shown in Figs. 3 and 4. We hope to study these angular distributions at several energies, particularly above and below the (p, n) thresholds for the Ni isotopes. A few measurements with a weighed target will also establish an absolute cross-section scale for these data. We hope to fit the data with the optical model and to study the effects of changing radius and neutron excess. It is also hoped that reliable absolute cross sections for elastic scattering from Cu at energies around 8-10 MeV will help to resolve the disagreements between different methods of measuring total reaction cross sections.

We would like to acknowledge the help of J. Wallace and F. P. Mooring and the tandem Van de Graaff staff in making this experiment possible.

Fig. 4. Elastic scattering of 8-MeV protons from Ni^{58} , Ni^{60} , Cu^{63} , and Cu^{65} .

I-98-30

Unbound Nuclear Levels in the KeV Region

(51210-01)

Carl T. Hibdon

FLUORINE

A study of the unbound levels of F^{20} has been continued.¹ The general features of these levels and tentative analyses of some of the levels up to about 150 keV neutron energy were given in previous reports.^{1,2} Some new data have been obtained in the regions of peaks Nos. 2, 6, 12, and 13 shown in Fig. 24 of reference 1, particularly in the wings of Nos. 2 and 6. The entire region from about 130-300 keV was also restudied. The additional data were needed in the use of a recently developed method of analysis.² Moreover, the energy dependence of the neutron scattering by the tantalum backing of lithium targets is now known.³ This correction has been applied to peaks Nos. 2, 6, 12, and 13 and to the peaks analyzed by the method given by Hibdon and Monahan.² The parameters obtained for these levels and other levels that could be analyzed are given in Table I.

Resonances in the 130-300 keV Region

The data obtained in the 130-300 keV region are shown in Figs. 5, 6, and 7. One sees many small peaks in Fig. 5 and many more with larger peak heights in Figs. 6 and 7. A correction for neutron

¹ C. T. Hibdon, Physics Division Summary Report ANL-6326 (March 1961), p. 35.

² C. T. Hibdon and J. E. Monahan, Physics Division Summary Report ANL-6432 (September - October 1961), p. 4.

³ C. T. Hibdon, Physics Division Summary Report ANL-6534 (April - May 1962), p. 25; Nuclear Instr. and Methods (to be published, 1962).

TABLE I. Levels of F^{20} derived from neutron reactions with F^{19} . The parameters J , ℓ , and Γ are the values obtained as a best fit to the data. The parameters for the s-wave levels used in the analyses are given also.

No.	E_r (keV)	J	ℓ	Γ (keV)
1	15.25			
2	27.35	2	1	0.30
3	31.9			
4	34.0			
5	38.0			
6	49.7	1	1	1.70
7	70.5			
8	87.8	0	1	4.00
9	96.0	1	1	5.50
10	100.0	2	1	1.10
11	102.4	1	0	3.00
12	113.2	0	1	1.20
13	121.7	0	1	1.00
30	200.2	0	0	2.0
43	246.0	1	0	1.8
44	247.8	1	0	0.4
48	267.7	1	0	1.4

Fig. 5. Neutron total cross section of fluorine in the 130-190 keV region. The curve shown by a solid line depicts the trend of the data obtained by flat detection. Solid circles represent the data obtained by self-detection. The loci of the theoretical single-level peak heights for $J = 0, l = 0, 1$ include only elastic scattering. Curve A represents the combination of the potential scattering and the wings of s-wave levels.

scattering by the tantalum backing of the lithium targets does not increase the heights of these peaks appreciably.³ A few of these peaks appear to be due to s-wave levels. The curves that appear to fit the data for the s-wave levels are shown in Figs. 5, 6, and 7. All of the plots for s-wave levels and the potential scattering were combined to obtain the curves labeled A in these figures. An attempt was made to analyze the peaks shown in Figs. 5, 6, and 7 by the method of Monahan and Hibdon.² However, the difference between the theoretical peak heights for successive values of J is quite large and the peak heights obtained by the analyses fail to come close to particular values for any J . Rather, they fall more

Fig. 6. Neutron total cross section of fluorine in the 184-244 keV region. The solid curve follows the trend of the flat-detection data. Points shown by solid circles show the trend of the self-detection data. The loci of the theoretical single-level peak heights for $J = 0$ and 1 include only elastic neutron scattering. Curve A represents the combined contributions of the s-wave levels and the potential scattering.

or less midway between the values for different J . Inelastic scattering is known to begin in this region⁴ and is apparently strong enough to reduce the peak heights considerably. Hence, $\Gamma_n < \Gamma$ for each peak and consequently the peak heights are reduced by the factor Γ_n/Γ . The regions covered by Figs. 6 and 7 exhibit peaks with larger heights than the ones shown in Fig. 5. However, the analyses still fail to yield peak heights near theoretical values for different J . The analyses do provide tentative sets of parameters for the levels shown in Figs. 5, 6, and 7 but the values of the spins are ambiguous and undoubtedly lead to erroneous values for the widths and the values of l . Therefore, an analysis of the resonances in the 130-300 keV region is deferred until a method is devised to include a reasonable estimate of the inelastic scattering.

A paper on the unbound levels of F^{20} up to a neutron energy of 300 keV is nearly ready to be submitted for publication.

⁴ J. M. Freeman, Phys. Rev. 99, 1446 (1955).

Fig. 7. Neutron transmission cross section of fluorine in the 240-300 keV region. The solid curve shows the variation in the flat-detection data. Points shown by solid circles were obtained by self-detection. The loci of the theoretical single-level peak heights for $J = 0-3$ include only elastic neutron scattering. Curve A represents the combined contributions of the s-wave levels and the potential scattering.

IV. PLASMA PHYSICSIV-10-4 Morphology of High-Frequency Plasmoids

(54100-01)

Albert J. Hatch

INTRODUCTION

The morphology of gaseous discharges and plasmas has always been an important facet in the study of their basic processes and mechanisms. Thus in the literature on dc glow discharges there has evolved a set of historical-descriptive names for the various visible features of discharges including the familiar positive column, Faraday dark space, negative glow, Crookes dark space, and others. Measurements of dc discharge parameters, such as the spatial distribution of charge density and potential, reveal variations that can be correlated with their visible structure. Since dc discharges have been studied rather intensively for over a century, it is not at all surprising that their morphological classification is considerably more advanced and well-established than that of high-frequency discharges which have only been studied rather sporadically since about 1925.

The purpose of the present report is to present a systematic photographic study of high-frequency plasmoids, to suggest a morphological nomenclature, and to point out some morphological characteristics that are pertinent to the mechanisms involved.

PLASMA DOMAINS

Correlation of the plasmoid photographs with the various high-frequency plasma mechanisms is facilitated by the

Fig. 8. High-frequency plasma domains. From data for plasmas produced in an atmosphere of dry air between aluminum electrodes, 23 cm in diameter and 15 cm apart, by rf potentials at a frequency of 15 Mc/sec.

revised domain map¹ shown in Fig. 8. This map represents a well-smoothed plot of several hundred observations made during the past three years. Nevertheless there are still some unmapped areas, mainly in transition zones where instabilities, detuning, and erratic nonreproducibility all combine to make observations difficult. Also missing from this map is a fine structure of subdomains, especially in the plasmoid regions, which are definitely present but have not yet been reproducibly delineated.

The map will not be discussed in detail here. However, in order to relate to a previous set of photographs² it is appropriate to

¹ For an earlier version see Fig. 6 in Physics Division Summary Report, ANL-6262, December 1960, p. 17-28.

² Ibid., Fig. 7.

point out that the Mode I and Mode II plasmas refer to the singly- and doubly-striated plasmas at pressures of $13\ \mu$ and $50\ \mu$, respectively, in reference 2. Consistency indicates that plasmas of the diffusion type, with two bright striations near each electrode plus a third centrally-located striation (usually of a different color and structure), as illustrated at $350\ \mu$ and $90\ \mu$ in reference 2, should be called the Mode III plasmas.

One other comment pertinent to the present use of the domain map is that the plasmoids occur at pressures of the order of 1 to 2 decades below the mean-free-path limit and the collision frequency transition as discussed by Brown and MacDonald.³ Although originally applied only to the diffusion mechanism of breakdown, these two concepts are nevertheless of considerable significance for plasmas. The mean-free-path limit is defined as the condition in which the electron mean-free-path is equal to the characteristic diffusion length of the plasma tube. For air, the data of Herlin and Brown⁴ indicate that the lower pressure limit for the diffusion breakdown mechanism to be operative in the present tube should be at $7.6\ \mu$. The collision-frequency transition is defined as the condition in which the elastic collision frequency between electrons and atoms is equal to the radian frequency of the applied field. From data obtained by Rose and Brown,⁵ again for air, this transition should occur in the present tube at $22\ \mu$.

³ S. C. Brown and A. D. MacDonald, Phys. Rev. 76, 1629 (1949).

⁴ M. A. Herlin and S. C. Brown, Phys. Rev. 74, 291 (1948).

⁵ D. J. Rose and S. C. Brown, J. Appl. Phys. 28, 561 (1957).

PLASMOID TERMINOLOGY

R. W. Wood,⁶ in his classic paper on high-frequency plasmoids, reported two types of plasmoid: a spheroidal type of high luminosity (bright green in pure O_2), and a lenticular type which was less luminous (pale green in O_2). Although the order in which they appeared as a function of rf potential depended on the exciting-electrode system being used, the transition from one type to the other was consistently abrupt. Another characteristic common to both types was that each appeared to be surrounded by a narrow dark sheath.

The present observations indicate that the spheroidal plasmoid is the only one that exhibits the dark sheath, that the darkness is relative rather than absolute, and that the degree of darkness depends on the conditions under which the plasmoid is formed. The spheroidal dark-sheath plasmoid can occur through a moderately wide range of pressures and applied rf potentials as shown in Fig. 8. The lenticular plasmoid occurs through a much narrower range of these parameters and exhibits no dark sheath. It is most likely that Wood's observation of a dark sheath for the lenticular plasmoid was due in part to electrode and discharge-tube configurations different from those used in the present work. The location of the small domain of the lenticular plasmoid with respect to that of the dark-sheath plasmoid is the reason for the name "low-pressure plasmoid." The terms "dark-sheath" and "low-pressure" allude to more basic properties of the plasmoids than do the terms "spheroidal" and "lenticular" which represent a shape parameter that is dependent mainly on configurations of the electrodes and plasma tube.

⁶ R. W. Wood, Phys. Rev. 35, 673 (1930).

DARK-SHEATH PLASMOIDS

All the plasmoids photographed and described here were established in dry air between plane parallel aluminum electrodes 26 cm in diameter and 15 cm apart at a frequency of 15 Mc/sec. Panchromatic film (Kodak Royal Pan) was used in a Speed-Graphic camera at $f/7.7$. Most exposures were at 10 sec. Because of the wide range of luminosities encountered, no attempt was made to maintain a systematic density scale among different photographs. The main criterion was a set of prints acceptable for half-tone reproduction.

A photograph of a typical dark-sheath plasmoid⁷ is shown in Fig. 9. The essential features of this photograph, as shown by the drawing in Fig. 10, are (A) the main body of the plasmoid (whitish in air). (B) the narrow dark sheath which gives the plasmoid its name, and (C) the wider Debye sheath that extends to the electrodes and tube walls. The electrodes are on the left and right edges of Figs. 9 and 10.

Semiquantitative information on the luminances of the various components of the plasmoid can be obtained from density measurements. A set of such measurements, made from the original negative used for Fig. 9, is shown in Fig. 11. The resolution of the densitometer was approximately a tenth of the width of the dark sheath, but there is an appreciable amount of "noise" due partly to the circumstance that the aperture of the densitometer was a

Fig. 9. Photograph of dark-sheath plasmoid. Plane parallel disk electrodes located on left and right sides of photograph. Frequency = 15 Mc/sec, electrode separation = 15 cm, pressure = 0.3μ in dry air.

⁷ A. J. Hatch, Proceedings of the Fifth International Conference on Ionization Phenomena in Gases (North Holland Publishing Company, Amsterdam, 1962), Vol. I, p. 748.

Fig. 10. Cross-sectional drawing of a dark-sheath plasmoid: (A) the main (luminous) body of the plasmoid; (B) the dark sheath; (C) the Debye sheath extending to the electrodes (left and right) and the plasma tube walls (top and bottom).

Fig. 11. Density of negative for plasmoid photograph in Fig. 9. Scale applies directly only to trace A. The subsequent traces B-F have each been successively raised by approximately 0.18 density unit to avoid overlapping.

pinhole rather than a slit. For facility in interpreting the densitometer measurements below, the trace along the z axis (axis of symmetry of the plasma tube and plasmoid) has been redrawn in Fig. 12 with most of the spurious irregularities smoothed out. Here it has been assumed that the density D of the negative can be represented by

$$D = \log_{10} (1 + aL), \quad (1)$$

where L is the luminance of the plasma glow and a is a normalizing constant.

A. Main Body of Plasmoid

This spheroidal region terminates sharply within approximately a millimeter, i.e., within less than 0.001 of an electron mean-free-path (M.F.P. ≈ 50 cm in air at 1μ). This is shown by the sharp rise in the density trace on the inner side of PLASMROID BOUNDARY in Fig. 11. By way of comparison, the boundary depth of the morphological divisions (such as the negative glow) in a dc glow discharge is of the order of one electron mean-free-path. The same is true of the striations in the high-frequency diffusion-type plasmas, such as Mode II and Mode III. It has not yet been possible to evaluate the luminance of the plasmoid body either directly or

Fig. 12. Luminance of the plasmoid shown in Fig. 9 taken from density trace of Fig. 11. L_{B1} is the luminance of the Debye sheath; L_P and L_{B2} are the luminances of the plasmoid body and Debye sheath as discussed in the text. The hatched crescent represents the finite luminance of the dark sheath. Coordinates z_i and z_o are the axial positions of the inner and outer edges of the dark sheath on the axis. The midplane is at 0 and the electrode is at 7.5 cm.

indirectly. Trial calculations with values of luminance from the Debye sheath background (as indicated by L_{B2} in Fig. 12), and with corrections for the shapes of the plasmoids, show that the luminance is constant to within 2-3% throughout the main body of the plasmoid.

The uniform luminance of the main body of the plasmoid and its sharp termination at the boundary can both be shown to be plausibly consistent with the assumed plasmoid mechanism. The present concept of this mechanism is that it is dominated by longitudinal electron-plasma oscillations of two types. One type is the class of axially nonsymmetric oscillations which can be driven by the applied rf potential; the other type is the class of axially and radially symmetric oscillations which can not be driven by the applied rf potential, but which possibly can be excited by cross-coupling to the nonsymmetrical oscillations.

One of the most interesting and significant of Wood's⁸ observations was that the spectrum of this main body consists of both atomic and molecular lines, whereas the spectrum of the sheath regions contains only atomic lines.

B. Dark Sheath

The dip in density at the dark sheath in Fig. 11 is definite and consistent, but not as great as had been expected from visual inspection of the plasmoid photograph and direct observation of the actual plasmoid. Similar densograms of other plasmoid photos show small dips such as these in some cases, plateaus in others, and in a few cases only a small inflection at the dark sheath. Since in all the photos the dark sheath appeared to be dark (in varying degrees), this outcome indicates that there is an "edge effect" optical illusion

⁸ R. W. Wood, Phil. Mag. 8, 207 (1929).

that enhances the dark appearance of the sheath when viewed by the eye. A typical shape of the dip in luminance in the dark-sheath region is the straight segment with reduced or reversed slope as shown between z_1 and z_0 in Fig. 12. If the luminance of the dark sheath were zero, the slope should change from negative on the right side of z_0 to infinity on the left side, then drop to finite positive values as shown by the lower broken curve representing the background from the Debye sheath. Thus the hatched and crescent-shaped area on Fig. 12 represents the luminance due to the dark sheath. The magnitude of this luminance is surprisingly large in view of the apparent darkness in the photograph of Fig. 9.

Three-dimensional viewing of an actual plasmoid enhances the impression of darkness of the dark sheath. Here, of course, the subjective nature of unaided vision is highly suspect and one's impressions must be evaluated carefully. However, direct vision has the added advantage of being binocular and also can incorporate receiver scanning, i.e., moving the head around to gain an impression of shape. This capability shows unequivocally that the dark sheath is a continuous three-dimensional shell that completely surrounds the plasmoid.

A proposed explanation of the dark sheath is that it represents a narrow zone in which the net rf E field (due to superposition of the applied E field and that developed by electron oscillations in the plasmoid) passes through a zero value.^{7,9}

C. Debye Sheath

The identification of the region C in Fig. 10 as a Debye sheath is based on the following considerations and measurements.

⁹ Physics Division Summary Report, ANL-6376, June 1961, pp. 36-46.

The axial length of the Debye sheath in the plasmoids is observed to be a function of both applied rf potential and of pressure through limited ranges of these parameters. In Fig. 13 the length of the Debye sheath (axial) depends strongly on V_{rf} at 0.2μ but not at 0.35μ . This dependence at 0.2μ is shown by the log-log plot in Fig. 14. The dependence of the Debye sheath on pressure is shown in the photos of Fig. 15 and the plots

Fig. 14. Axial length of Debye sheath in dark-sheath plasmoids as a function of applied rf potential. The data were determined from photographs, three of which are shown at 0.2μ pressure in Fig. 13.

Fig. 13. Photographs of dark-sheath plasmoids. Electrodes are identifiable on left and right sides of each photo by reflected light from plasmoid. Electrode separation = 15 cm, applied frequency = 15 Mc/sec, pressures and applied rf potentials as indicated.

Fig. 15. Photographs of dark-sheath plasmoids. Electrodes are identifiable as in Fig. 13. Electrode separation = 15 cm, applied frequency = 15 Mc/sec, applied rf potential = 81 V, pressures as indicated.

of Fig. 16. Thus in the range of rf potentials and pressures considered here, the $+\frac{1}{2}$ and $-\frac{1}{2}$ slopes in Figs. 14 and 16, respectively, indicate that the length of the Debye sheath is proportional to $(V_{rf}/p)^{1/2}$. According to theory,¹⁰ the length of the Debye-Hückel shielding distance can be written as

$$\lambda_D = 6.9(T/n)^{1/2}, \quad (2)$$

where T and n are the electron temperature (Maxwellian) and electron density, respectively.

Now it is certainly plausible that the electron temperature increases as the applied rf potential increases, but the functional relation between these

Fig. 16. Axial length of Debye sheath in dark-sheath plasmoids, plotted as a function of pressure. Open circles represent data from photographs, four of which are in Fig. 15, applied rf potential = 81 V. Crosses represent data obtained by direct visual observation of plasmoids, applied rf potential = 76 V. Frequency = 15 Mc/sec and electrode separation = 15 cm for all data.

¹⁰ L. Spitzer, Physics of Fully Ionized Gases (Interscience Publishers, Inc., New York, 1956), p. 17.

two parameters is not known for the plasmoid case. However, a linear dependence can be assumed as a first-order approximation. It is also plausible that the electron density increases as the pressure increases, but here also the functional relation is not known. Again, however, a linear dependence can be assumed as a first-order approximation. If one now admits these two first-order linear approximations over a suitably limited range of parameters, then it is possible to identify the observed dependence on $(E_{rf}/p)^{1/2}$ with the theoretical Debye-Hückel dependence on $(T/n)^{1/2}$ as in Eq. (2). This tenuous argument is the basis for the tentative identification of this sheath as a Debye sheath. This argument actually holds up quite well on a quantitative basis. Thus, if the plasmoid has an electron temperature of $150\,000^\circ$ (corresponding to an electron energy of 15 eV^{11}) and a cutoff electron density¹² of $2.78 \times 10^8\text{ cm}^{-3}$ (corresponding to the applied frequency of 15 Mc/sec), the length of the Debye sheath is $\lambda_D = 1.6\text{ cm}$. This corresponds to the axial length of the sheath at a pressure of about $1\text{ }\mu$ in Fig. 16.

In the photographs in Figs. 13 and 15, it is evident that at the higher pressures and potentials the luminance of the Debye sheath is high and tends to obscure the dark sheath. From the photographs in Fig. 15 it appears that the width of the dark sheath increases slightly as the pressure is reduced. In the range of very low rf potential near the maintaining boundary for the dark-sheath plasmoids, the dark sheath evidently disappears as shown in the two bottom frames of Fig. 13. Although the reason for this is as yet unknown, it is suspected that what actually happens is that either the Debye sheath disappears or that the Debye sheath

¹¹ E. R. Harrison, J. Electronics and Control 5, 319 (1958).

¹² R. Geller, Compt. rend. 249, 2749 (1959).

and the plasmoid dark sheath become identical. This question is unlikely to be resolved until more is learned about the features distinguishing these two types of sheaths.

No enlightening information on the Debye sheaths has yet been obtained from the density traces in Figs. 11 and 12.

LOW-PRESSURE PLASMOIDS

Photographs of the lenticular type of plasmoid, similar to those originally reported by Wood, are shown in Fig. 17. The transition

Fig. 17. Photographs of low-pressure plasmoids. Electrodes are located as in Figs. 13 and 15. Electrode separation = 15 cm, applied frequency = 15 Mc/sec, pressure = 0.15μ , applied rf potentials are as indicated.

between these low-pressure plasmoids and the dark-sheath plasmoids is always abrupt, but the domains overlap because of pressure hysteresis. That is, at an rf input power at which the transition with increasing pressure occurs at about 0.2μ , the transition with decreasing pressure occurs at about 0.1μ . This transition is indicated in Fig. 8 by the heavy broken line. Studies of the electrical characteristics show that those of the low-pressure plasmoids are very similar to those for multipacting.

This is consistent with the photographs which show the low-pressure plasmoid superposed on the fairly uniform bluish but sheathless glow typical of multipacting. It is also consistent with the fact that this type of plasmoid is not observed by Harrison¹¹ and Geller,¹² both of whom use rf exciting fields incapable of producing multipacting. Densitometer measurements made on these plasmoids indicate that the plasmoid dark sheath is not present here. The whitish glow of the low-pressure plasmoids in air is extremely faint in comparison with that of the dark-sheath plasmoids, and they usually can only be seen when viewed edge-on in the radial direction. This is also in contrast to the dark-sheath plasmoids which are equally visible from all directions.

The low-pressure plasmoid can be made to become as thin as desired (up to the ability of the eye to detect it), and under favorable circumstances it has been observed in the form of a wafer about 1 mm thick and 2 - 5 cm in diameter. Thus it is more in the nature of a very tenuous striation rather than a plasma entity. It is possible that it may be a sort of precursor of the dark-sheath plasmoid and that it competes weakly against multipacting at these low pressures.

HIGH-POWER PLASMAS

Above the dark-sheath plasmoids there is an uncharted transition zone in Fig. 8 characterized by plasma instabilities that are attributed to an unknown combination of effects such as mode jumping, rf circuit detuning, and electrode outgassing. This zone can be crossed merely by increasing the input rf power sufficiently and keeping the exciting circuit as well tuned as possible. The high-power plasmas produced by the high rf potentials (above 1 kV) and

power of the order of several hundred watts have some of the visual characteristics of both the dark-sheath plasmoids and the Mode I plasmas. Photographs of these high-power plasmas are shown in Fig. 18. At the

Fig. 18. Photographs of high-power plasmas. Electrodes are located as in Figs. 13, 15, and 17. Electrode separation = 15 cm, applied frequency = 15 Mc/sec. pressures and applied rf potentials are as indicated.

lowest pressure (0.8 μ) the plasma boundary is very poorly defined. At the intermediate pressures (2.2 μ and 4.0 μ) the left side appears to be quite well defined but the right side is diffuse. This is because the camera was purposely located off-center in order to show the extreme sharpness of one of the boundaries. The boundaries are actually the same on both sides, are extremely sharp, are very nearly flat, and give the plasma the appearance of a brightly glowing slab. There is no comparable radial boundary and the plasma extends almost continuously to the radial edge of the discharge tube where the nonuniform thickness of the pyrex walls obscures the details for tangential viewing angles. It is mainly for this reason that these plasmas are not considered to be plasmoids. Comparison of the structure of these plasmas with that of the dark-sheath plasmoids indicates that the symmetric type of electron-plasma oscillation does not occur in the high-power plasma and that the nonsymmetric

oscillations are the only type that do occur. This high-power plasma has been tentatively called "normal" because the internal rf field is merely attenuated rather than reversed as in the case of the dark-space plasmoid.⁹

V. THEORETICAL PHYSICS, GENERALV-12-1 Seniority Mixing in $1f_{7/2}$ Nuclei

(51210-01)

R. D. Lawson and B. Zeidman

For target nuclei in which the $1f_{7/2}$ neutron shell is filling,^{1,2} it has been found that more than one prominent $\ell = 3$ transition is observed in neutron pickup reactions. On the basis of all the data, one can show that ascribing each of the peaks to a different orbital does not provide a satisfactory explanation of the results. If the wave functions describing nuclei in which the $1f_{7/2}$ shell is filling with neutrons and protons have well-defined isotopic spin and seniority, then the (d,t) pickup reaction on an even-even target should populate only two levels with $\ell = 3$ in the odd-A daughter, namely, the $I = \frac{7}{2}$ states with seniority one and isotopic spin $T \pm \frac{1}{2}$. If the usual model of pickup reactions is to be retained, then a reasonably satisfactory analysis of the results is possible provided seniority is not a good quantum number in the $1f_{7/2}$ shell (i.e., the nuclear states have mixed seniority). All the strong $\ell = 3$ transitions observed may then be considered as arising purely from pickup of $1f_{7/2}$ neutrons.

An alternative to the seniority classification for nuclear states is provided by the Elliott generating procedure.³ In this method, the lowest energy eigenvector of spin I is assumed to be given by

¹ J. L. Yntema, Phys. Rev. (to be published).

² B. Zeidman and T. H. Braid, Bull. Am. Phys. Soc. 7, 315 (1962).

³ J. P. Elliott, Proc. Roy. Soc. (London) A245, 128 (1958).

$$\psi_{MT_z}^{IT(K)}(x) = (2I + 1) C_K^I \int dR D_{MK}^I(R) \chi_K(Rx),$$

where C_K^I is a normalization constant, $D_{MK}^I(R)$ is the rotation matrix, and the coordinate system Rx is oriented with respect to the laboratory system x . The N -particle determinant χ_K is constructed by filling the lowest Nilsson orbits of the $1f_{7/2}$ shell for either positive or negative deformation. On the basis of wave functions constructed in this way, fractional parentage coefficients can be evaluated. The strengths given in Table II are proportional to the squares of these coefficients.

The theoretical and experimental results are given in the table. The calculations have been performed by generating from both signs of the deformation as well as for the pure seniority wave functions. The calculated values are for transitions to the lowest states of spin I in the final nucleus. The experimental results are obtained from (d,t) reactions initiated by 21.5-MeV deuterons.^{1,2} There is good agreement between the present calculations and the experimental results for most transitions. The positive deformation usually is preferred. The most flagrant disagreement is the transition to the ground state of $Ti^{46}(d,t)Ti^{45}$; but even here the seniority value is no better. For the $Ti^{49}(d,t)Ti^{48}$ reaction, both the mixed-seniority wave functions and the experimental data indicate that the bulk of the transition strength proceeds to states other than the lowest 0^+ , 2^+ , 4^+ , and 6^+ states. The sum of these strengths, however, exhausts the sum rule for wave functions of pure seniority. The amount of seniority mixing is directly measured by the $Ti^{50}(d,t)Ti^{49}$ reaction, which shows the mixing to be about 50%.

TABLE II. Strengths of transitions. The strengths of transitions to the lowest state of spin J in the final nucleus are calculated by use of wave functions generated from positive deformation, negative deformation, and seniority. The last column lists the experimental value for these transitions.

Target	Level in the final nucleus		Strength			
	Energy	Spin	+ Deformation	- Deformation	Seniority	Experiment
Ti ⁴⁶	0	7/2 ⁻	3.27	3.00	3.33	2.15
Ti ⁴⁷	0.88	2 ⁺	0.78	0.43	—	0.57
	2.07	4 ⁺	0.88	1.27	—	0.86
	3.30	6 ⁺ (?)	0.08	0.06	—	0.13
Ti ⁴⁸	0.16	7/2 ⁻	3.74	3.67	5.60	2.45
Ti ⁴⁹	0	0 ⁺	0.25	0.25	0.25	0.23
	0.98	2 ⁺	0.88	0.45	1.19	0.68
	2.33	4 ⁺	0.50	0.82	2.14	0.54
	3.30	6 ⁺ (?)	0.05	1.37	3.09	(2.30)
Ti ⁵⁰	0	7/2 ⁻	4.90	4.90	7.71	4.05
Cr ⁵²	0	7/2 ⁻	3.31	4.23	7.20	3.58
Fe ⁵⁴	0	7/2 ⁻	3.75	5.52	6.00	4.43

PUBLICATIONS SINCE THE LAST REPORT

PAPERS

TIME REVERSAL AND SUPERSELECTION

H. Ekstein (Project V-42)
 Nuovo cimento 23, 606-615 (February 1, 1962)

POLARIZATION OF NEUTRONS IN SCATTERING FROM LIGHT NUCLEI AND IN THE $\text{Li}^7(\text{p}, \text{n})\text{Be}^7$ REACTION

A. J. Elwyn and R. O. Lane (Project I-18)
 Nuclear Phys. 31, 78-117 (January 1962)

POLARIZATION AND DIFFERENTIAL CROSS SECTION FOR NEUTRON SCATTERING FROM SILICON

R. O. Lane, A. J. Elwyn, and A. Langsdorf, Jr. . . (Project I-18)
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Abstracts for the meeting of the American Physical Society, Evanston,
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$\text{N}^{14}(\text{d}, \alpha)\text{C}^{12}$ REACTION (Project I-25)

R. G. Allas, T. H. Braid, L. L. Lee, Jr., and J. P. Schiffer
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G. E. Thomas and L. M. Bollinger (Project I-2)
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TARGETS

C. T. Hibdon (Project I-98)
Nuclear Instr. and Methods

A THIN dE/dx COUNTER WITH LARGE APERTURE

J. A. Weinman and R. K. Smither (Project I-16)
Rev. Sci. Instr. (June 1962)

PERSONNEL CHANGES IN THE ANL PHYSICS DIVISION

NEW MEMBERS OF THE DIVISION

Resident Research Associates (Summer)

Dr. Calvin M. Class, Associate Professor, Rice University.

Measurement of lifetimes of nuclear states by recoil methods. Came to Argonne on June 14, 1962. (Host: S. S. Hanna.)

Dr. Suraj N. Gupta, Distinguished Professor of Physics, Wayne

State University, Detroit, Michigan. Theory of elementary particles. Came to Argonne on June 18, 1962. (Host: M. Hamermesh.)

Dr. Kurt Just, Associate Professor of Physics, University of

Arizona, Tucson, Arizona; on leave from the Free University of Berlin. Gauge invariance in electrodynamics and gravitation. Came to Argonne on June 1, 1962. (Host: M. Hamermesh.)

Dr. Lu Sun Liu, Lecturer in Physics, Northwestern University.

High-energy particle physics and complex angular momenta. Came to Argonne on June 14, 1962. (Host: M. Hamermesh.)

Dr. Irving Michelson, Professor of Mechanical Engineering,

Illinois Institute of Technology. Studies of energy transfers induced by radiofrequency discharge in air. Came to Argonne on June 18, 1962. (Host: A. J. Hatch.)

Dr. Bishan P. Nigam, Associate Professor, University of Buffalo.

Spin-orbit interaction in nuclei. Came to Argonne on May 31, 1962. (Host: M. Hamermesh.)

Dr. J. Reid Patterson, Professor and Head of Physics Department,

Rockford College. Research with the fast chopper.

Came to Argonne on June 6, 1962. (Host: L. M. Bollinger.)

Dr. Fred E. Stafford, Assistant Professor of Chemistry, North-

western University. Mass spectrometric study of the reaction of vapors with condensed phases at

high temperatures. Came to Argonne on June 13, 1962. (Host: J. Berkowitz.)

Resident Research Associate (Post-Doctoral)

Dr. E. Brooks Shera, Instructor in Physics, Western Reserve

University. Nuclear spectroscopy of short-lived radionuclides. Came to Argonne on June 14, 1962.

(Host: S. B. Burson.)

Resident Student Associates (Summer)

Mr. Allan D. Carlson, graduate student, U. of Wisconsin. Working

with T. H. Braid on the development of solid-state detectors and on gamma-ray spectroscopy. Came to

Argonne on June 4, 1962.

Mr. Robert J. Freiberg, graduate student, University of Illinois.

Working with A. J. Hatch on experimental investigations of high-frequency plasmas and plasmoids.

Came to Argonne on June 6, 1962.

Mr. Harvey Leff, graduate student, State University of Iowa. Work-

ing with N. Rosenzweig on the statistical theory of energy levels. Came to Argonne on June 14, 1962.

Mr. James C. Pool, graduate student, State University of Iowa.

Working with J. M. Cook (AMD) on the mathematical foundations of quantum field theory. Came to Argonne on June 14, 1962.

Student Aides (Summer)

Mr. Timothy Hart, Knox College. Working with S. S. Hanna on research with the Moessbauer effect. Came to ANL on June 12, 1962.

Mr. George Rieke, Oberlin College. Working with G. J. Perlow on studies of the Moessbauer effect. Came to ANL on June 7, 1962.

Mr. Gene Rugotzke, Wisconsin State College, Eau Claire. Working with S. Wexler on the construction and use of a mass spectrometer for the study of the ionization and excitation induced by very energetic, massive ions from the Van de Graaff. Came to ANL on June 7, 1962.

Mr. Brian M. Salzberg, Yale University. Working with R. K. Smither and A. P. Magruder on the analysis of data on gamma rays from neutron capture in Sm and Te. Came to ANL on June 13, 1962.

Mr. Gene Sprouse, Massachusetts Institute of Technology. Working with R. K. Smither on measurements of capture gamma rays from tellurium with the bent-crystal spectrometer at CP-5. Came to ANL on June 13, 1962.

Mr. John B. Van Zytveld, Calvin College, Grand Rapids, Michigan. Working with J. L. Yntema on analysis of data on (d,p) reactions on Ti and Bi and on the construction of control devices for the 60-in. scattering chamber. Came to ANL on June 5, 1962.

Mr. Ronald E. Zelac, University of Illinois. Working with J. Berkowitz on (1) setting up an experiment to measure the ionizing efficiency of electrons and/or (2) studying the reactions between excited or ionized metal atoms and a gas as a function of the partial pressures, the ionizing voltage, and the current. Came to ANL on June 19, 1962.

Technician

Mr. Louis J. Chiricotti joined the Physics Division on June 19, 1962 as a Research Technician Jr. with R. S. Preston and R. K. Smither.