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RESEARCH ON THE SIZE AND SHAPE OF LARGE MOLECULES  
AND COLLOIDAL PARTICLES

by

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FINAL REPORT

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## A. SUMMARY OF WORK DONE

This final report encompasses the work done under Contract NONR 736(00) from December 1, 1951 to April 30, 1961 and, subsequently, under Contract NONR 3511 (00) from May 1, 1961 to May 31, 1970 and, finally, under Contract N 00014-70-C-0410 from June 1, 1970 until November 30, 1971.

### I. DETERMINATION OF PARTICLE SIZES AND SIZE DISTRIBUTIONS FROM LIGHT SCATTERING

The work carried out under the auspices of the Office of Rubber Reserve of the War Production Board, by the late Professor P. Debye at Cornell University and by the writer and his group at the University of Chicago (1943-1946) had shown the promise inherent in light scattering measurements for determining both molecular weights and particle sizes. While, after the last war, Professor DEBYE'S group and, subsequently, a fast increasing number of other research groups, stimulated by DEBYE'S fundamental, trail blazing work, concentrated on developing the analytical potential of the light scattering method for determining molecular weights and molecular weight distributions, the writer and his group, with the decisive support of the Office of Naval Research endeavored to develop further the light scattering theory for compact spherical bodies of any size initiated by MIE, in 1908, and at the same time to design apparatus and develop experimental techniques so as to make the light scattering method a modern, accurate and precise tool for determining particle sizes. The results of this first phase of work are described in TECHNICAL REPORTS 1, 2, 3, 5, 8, 9, 10, 13, 14, 15, 16, 17, 19, 21, 22, 24, 26, 27, 29, 30a, 31, 32, 33, 35, 39, 40, 45, 49, 53, 54,

55 (list I) and in PUBLICATIONS-1, 2, 3, 4, 6, 9, 14, 15, 16, 17, 18, 21, 23, 24, 25, 26, 29, 30, 32, 33, 37, 38, 42, 43, 44, 45, 47, 50, 51, 52, 55 (list II).

It was found that the particle sizes obtained in monodisperse colloidal dispersions of spheres (using polystyrene latices) were, in both accuracy and precision, superior to those obtainable by other methods on using the techniques developed and the theoretical data computed in this laboratory. The overriding advantage, however, turned out to be the speed with which results could be obtained and the fact that the measurements did not require removing the particles from their environment (as is necessary in electron microscopy) or subjecting the system to the possibly coagulating effects of forced translation as in centrifugation (orthokinetic coagulation).

In the case of heterodisperse systems, the light scattering method could furnish only average particle sizes. This shortcoming of the light scattering method led to the second phase of research in this laboratory. It was concerned with establishing the theory and developing the technique for determining size distributions. Subsequent tests on heterodisperse polystyrene latices showed that the results were in excellent agreement with the results obtained by electron microscopy. This work is described in the TECHNICAL REPORTS- 4, 12, 34, 36, 42, 43, 47, 50, 51, 52, 60, 61, 61a, 66 (list I) and in PUBLICATIONS- 39, 40, 41, 46, 48, 49, 61, 63, 66 (list II).

This new technique of determining size distributions and the collection of computer data which facilitated its use subsequently found wide application both in academic research and in industry. One important problem remained

to be solved however: the compilation of size distributions by the new technique was very time consuming. Attempts to resolve this problem initiated the third phase of this project. It involved feeding the experimental data directly into the computer, and having the computer determine the distribution. The solution of this problem is to be described in Papers 1 and 2 (list III).

The determination of size distribution curves in heterodisperse systems by means of the methods described is particularly attractive in those cases where other methods are not applicable or are not reliable. This applies particularly to emulsions where electron microscopy cannot be considered except on applying risky tricks. Use of the light scattering technique to determine the size distributions and their changes, in moderately heterodisperse emulsions gave very encouraging results. See paper 2 in list III.

The next question considered was whether or not it would be possible to extend the application of the technique developed to systems which have a very broad distribution of particle sizes. Such systems had heretofore not been considered as suitable objects for analysis by the light scattering method. Unfortunately, emulsions often have size distributions which are quite wide. Attempts were therefore initiated to extend the range of applicability of the light scattering method to very heterodisperse systems. Preliminary theoretical work and preliminary experiments lead to the encouraging result that even quite broad size distribution curves may be amenable to quantitative analysis on investigating the spectra of certain light scattering quantities as

a function of the angle of observation. Papers 3,14 (list III). For this purpose, an extensive modification of the existing experimental equipment was begun in 1971. Its completion remains in abeyance.

## II. DETERMINATION OF THE SHAPE OF RIGID PARTICLES AND MACRO-MOLECULES FROM LIGHT SCATTERING IN FLOWING SYSTEMS

A little over fifty years ago, Freundlich and Diesselhorst (Physik. Z., 16, 422 (1915) ) found on observing, visually, light scattered from incident polarized light by colloidal suspensions of crystals, that streaming produced pronounced differences between suspensions of rodlike and platelike particles. This work was not followed up during the many intervening years, probably due to its having been published in a generally little noticed periodical. The method seemed to have great analytical potential and it was therefore decided to develop it into a sensitive tool for determining the shape of non-spherical objects quantitatively in those cases where alternate existing methods, such as electronmicroscopy, could not be expected to give conclusive information. The development of this new quantitative method proceeded along both theoretical and experimental lines. As regards the experimentation, an apparatus was developed which has been described in detail. Technical Report 65 (list I) and Publications 31, 65 (list II). The theory was developed, in connection with the present project, primarily by Professor A. F. Stevenson. (Technical Reports- II, 23, 41, 48, 63 (list I) and Publications - II, 28 (list II) and A. F. Stevenson, J. Chem. Physics, 40, 4545 (1968) ).

Most recently, the Stevenson theory was generalized, by Professor Nakagaki and the writer and, furthermore, electronic computations were carried out on the basis of which a rapid translation of observed quantities into numerical dimensions of rigid non-spherical scatterers is possible. Papers 9 and 11 (list III). Preliminary experiments, carried out with solutions of tobacco mosaic virus were encouraging since here, where electron microscopy is a reliable method, the results obtained on the length of the rodlike virus agreed with those obtained by electron microscopy (Technical Reports 44, 46 (list I), and Publications - 36 (list II)). Subsequently, the method was successfully applied to nearly monodisperse colloidal solutions of ironoxide crystals whose length was varied systematically between 1/3 and 1 micron. (Technical Report - 62 (list I), Publications 59, 60 (list II) and Paper 5 (list III) ). Rigid particles whose largest dimension is smaller than 1/3 micron, could not be investigated quantitatively with the apparatus without further improvements which were applied recently and which will be discussed presently.

### III. DETERMINATION OF THE DEFORMABILITY OF MACROMOLECULES FROM LIGHT SCATTERING IN FLOWING SYSTEMS

An important second reason for the development of the new technique of flow light scattering measurements was the prospect of obtaining information on the deformability of flexible macromolecules and, therefore, on their "molecular elasticity" which could not be obtained in a similar direct way by any other method. The theory of the effect of flow upon

the light scattering of freely flexible macromolecules was developed in this laboratory in conjunction with Professors Peterlin and Nakagaki (the work of the former was supported by a supplemental grant to the writer by the Office of Ordnance Research). Technical Report 64 (list I), several reports to OOR and Publications - 12, 13, 22, 27, 64 (list II).

Experimentation showed that the theoretically predicted increment in light scattering produced by deformation of macromolecules in flow existed, but the effect found with the original apparatus was too small to be of interest. Therefore, improvements of the apparatus became mandatory. The first improvement consisted of the replacement of the high pressure Hg-arc originally used by a Helium-Neon-laser and by introducing a novel type of device, constructed from the plans of the writer, which made it possible to carry out investigations with both linearly polarized light and right and left circularly polarized light. By means of this improved apparatus, it became possible to measure quantitatively the deformation of macromolecules. It was found to be particularly pronounced with those macromolecules (such as polyacrylamide) which have been found to be very effective in suppressing turbulence. The preliminary results obtained have been published (Technical Report 64 (list I); Publication 64 (list II); Paper 4 (list III).) One remaining problem was that the flow effect was well measurable only on high molecular weight materials. In order to extend measurements to macromolecules of molecular weight of 500,000 or less, further improvements of the apparatus became necessary. First of all, the IP 21 photo multiplier tube was

was replaced by the new, experimental RCA Quanticon tube. In addition, the Photovolt instrument was replaced by a newer model of ten-fold higher sensitivity. Both changes led to a hundred fold increase in the overall sensitivity of the instrument. In order to take full advantage of this improvement, an additional modification of the electronic instrumentation was initiated namely the transformation of the readout from a direct readout to a differential readout in order to eliminate the effect of fluctuations in the intensity of the laser. The latter improvement could not be completed by the time of termination of the contract. A further technical improvement in the apparatus that, however, was completed, was the replacement of the concentric cylinder formerly used, by an improved model which allowed one to scan, instead of an angular range of  $40^{\circ}$ , an angular range of  $90^{\circ}$ . This made it possible, in principle, to extend the angular measurements over the entire range which is of interest from the theoretical point of view.

The improvements which were completed, made it also possible to extend the range of sizes of colloidal crystals amenable to quantitative dimensional analysis appreciably below the former limit of  $1/3$  micron mentioned earlier in this report. Except for a few exploratory experiments which yielded positive results, no work in this range of small colloidal particles and/or small non-spherical viruses had been started as yet at the time of termination of the contract.

IV. DETERMINATION OF THE MOLECULAR SHAPE OR CONFORMATION  
FOR MOLECULES OF MOLECULAR WEIGHTS < 50,000, FROM  
DEPOLARIZATION OF SCATTERED LIGHT

The use of light scattering of flowing systems is limited in its application to particle sizes and molecular weights large enough so that a quantitatively detectable degree of orientation occurs. This cannot be expected if the molecular weight is less than about 50,000 or the longest dimension of a non-spherical particle is smaller than about 50 A. U. unless unusually high shear rates are applied which generally are excluded because of technical difficulties if laminary flow is to be preserved. Many protein molecules and a large number of other biologically important molecules have molecular weights smaller than defined by these approximate limiting values. Flow light scattering was therefore not promising for low molecular weight solutes. In order to make non-spherical objects of such relatively small dimensions accessible to precise dimensional evaluation by light scattering, depolarization measurements were considered to be most promising. To that effect a theory of light scattering had to be developed first since the only existing pertinent theory for non-spherical scatterers of any relative refractive index, that of Rayleigh, is limited to objects negligibly small compared to the wavelength of light used. Professor A. F. Stevenson developed this theory within the framework of the present project. (Technical report 11, 63 (list I); A. F. Stevenson, J. Chem. Phys., 40, 4545 (1968).) A theoretical test, by the writer, of the equations arrived at by Professor Stevenson, showed

that in the case of visible light, the upper limit of application of the Stevenson theory should not be reached before the largest dimension of the scattering material is about one fifth of the wavelength of the light used. Consequently, the theory can be expected to encompass all systems containing not only low molecular weight molecules, but also macromolecules up to a molecular weight of about 200,000. Thus the new theory promised to make available an entirely new range of dimensions for precise analysis by means of light scattering. After the untimely death of Professor Stevenson, the new theory was generalized and evaluated in detail in collaboration with Professor Nakagaki who spent a sabbatical year in the writers laboratory for the second time. The theoretical results arrived at vindicated the expectation that depolarization measurements should allow one to obtain very precise results on the dimensions of non-spherical objects considered as either prolate or oblate spheroids without one's having to make, a priori, any assumption as to which of the two types is present in a given instance. Computer data of this work are about to appear in book form. (Publication 67 (list II); 12 (list III) ) Detailed theoretical results will be published in a series of forthcoming papers. Papers 7, 8, 12 (list III). Some of them have been presented within the framework of a Main Lecture at the 1969 Symposium on Light Scattering held at the Institute for Macromolecular Chemistry in Prague (Czechoslovakia) under the auspices of IUPAC. Experimental work also was started with the objective of adapting our equipment to precision measurements of the three types of depolarization involved. This work has now been interrupted until further support can be found.

V. OTHER RESEARCH CARRIED OUT WITHIN THE FRAMEWORK OF THE  
ONR CONTRACT

Several investigations were carried out on subjects other than those covered by the subject title of the contract. Some of them were closely related to and therefore important in connection with the main topic(s). Most of them were theoretical investigations (V, 2, 3, 4, 5, 6 and part of 7 and 9). The experimental work (V, 1, 8 and parts of 7 and 9) was carried out during periods of time when, for one reason or another (e. g., repairs), the light scattering equipment was out of order or was being modified.

1. Study of Turbulent Flow by Means of Light Scattering

During the experiments with colloidal suspensions of ironoxide crystals, referred to in section AII, it was noted that the formation of vortices near the critical rate of shear could be detected quite easily. Therefore, the effectiveness of additives in suppressing turbulence could be evaluated accurately. This study being outside of the primary objective, it was not followed up, although it was recognized that this new method of turbulence research was most promising from the practical point of view. Some of the results were given in several Progress Reports to ONR. In addition, a preliminary note has been published - Publication 59 (list II). A detailed account is under preparation, Paper 6 (list III).

2. Visibility of Light Sources in Fog

A theoretical study concerned with the "visibility of luminous objects through fog in absence and presence of search lights" was carried out on the basis of

the Mie theory. An abstract of the results, which are potentially very significant for air traffic in case of radar malfunctions, has been published. (Publication 30 (list I). A detailed publication is forthcoming (Paper 15, list III).

3. Angular Location of Scattering Maxima and Minima, Turbidity Maxima, and their Practical Significance

It was found that a relatively simple semi-empirical equation satisfies, in the case of monodisperse systems, the angular location of lateral scattering maxima and minima which are observed when the diameter of the scattering spheres approaches the dimension of the wavelength used (Technical Report 33 in list I and Publication 32 in list II). A recent reinvestigation of this subject, on the basis of more comprehensive computational data, confirmed this equation, and allowed one to generalize it (Paper 13 in list III). These maxima and minima change in amplitude and shift in angular location with the degree of heterodispersion. Extensive computational work was under way recently with the objective of making these changes the basis for a rapid determination of size distribution curves in heterodisperse sols and aerosols. If a critical survey of the results obtained thus far seems to warrant it, they will be published without waiting for financial support needed for continuation of the computational analysis. (Paper 14 in list III). In addition to the maxima and minima in lateral scattering, the turbidity maximum was the subject of attention, particularly since by means of the proper procedure, one can use it in order to obtain

both size and refractive index of the scattering material (Technical Report 5, list I; Publication 6, list II). Extensive further investigations showed that equations developed in this connection (Paper 16, list III), in fact, allowed one to obtain accurate results on both particle size and refractive index of polystyrene in latices. (Paper 17, list III). This possibility is particularly intriguing in connection with the problem of characterizing particulate interstellar matter of dimensions comparable to the wavelength of radiation used.

#### 4. Range of Validity of the Debye and the Rayleigh Light Scattering Equations

The Mie equations allow one to evaluate particle sizes of spherical scatterers of any relative refractive index, real or complex, and of any size relative to the dimensions of the wavelength of light used. They are not needed if the scatterers are sufficiently small relative to the wavelength. In order to limit the application of the rather complicated functions of the Mie equations to those cases where they are absolutely needed, the practical limits for use of the much simpler Rayleigh equation were established by a suitable theoretical approach. (The results were given in Technical Reports 56 and 58 (list I) and Publications 53 and 54 (list II). The results also furnished explicitly the upper limits of molecular weights that may be calculated from light scattering data by means of the well-known Debye equation if the error that can be tolerated in the result is 1, 2, 5, or 10%.

#### 5. Extension of the Rayleigh-Gans Equation of Light Scattering

The only limitation of the Mie equations of light scattering is that they are applicable only to spherical and quasispherical isotropic bodies. For non-spherical bodies, the most useful equation is that referred to generally as the Rayleigh-Gans equation unless one operates with very special systems (extreme axial ratio of the scatterer or scatterers which are much larger in one dimension than the wavelength of the radiation used). The shortcomings of the Rayleigh-Gans equation are that (1) it gives strictly correct results only if the refractive index of the scatterers differ very little from that of the surrounding medium; (2) it cannot account for the depolarization of light scattered by non-spherical bodies, a phenomenon which, however, is of major potential analytical importance. Significant progress was made in connection with the present project in reducing both problems. A new equation was developed which, hopefully, can be evaluated by computer provided financial assistance can be obtained for the programming which will be rather difficult and time consuming in view of the complexity of the equation. The equation and its implications have been published some time ago. (Technical Report 48 (list I) and Y. Ikeda, "Extension of the Rayleigh-Gans Theory", in "Electromagnetic Scattering", Edited by M. Kerker, Pergamon Press, New York, 1963)

#### 6. Recalculation of the Peterlin-Stuart Functions

An optical method of major analytical importance in macromolecular chemistry and physics is the measurement of streaming birefringence. This method and that of flow light scattering by rigid non-spherical bodies are

closely related inasmuch as the evaluation of data obtained is based upon the use of the Peterlin-F Stuart functions given approximately 30 years ago. These rather complicated functions were evaluated many years ago by Scheraga and associates (Cornell University). A series of approximations were then necessary in the computer program in view of the limited capabilities of computers at that time. These functions have now been recomputed using the IBM 360. It is planned to publish the results in a series of Tables (Paper 10 (list III)). Besides being important for the work discussed in section (II) (if this work can be continued), the recalculated data will make it possible for all those workers concerned with streaming birefringence to evaluate their results more quantitatively than was possible heretofore.

#### 7. True and Apparent Refractive Index of Colloidal Materials

During the early investigations of light scattering by synthetic lattices, within the framework of the present project, it was noticed that the refractive index obtained directly from interferometric measurements on the lattices was an apparent quantity only which approached the true refractive index of the latex particles, if their diameter was less than about  $1/2$  the wavelength of the radiation used. A systematic investigation on monodisperse lattices of systematically varied particle diameter furnished an empirical relationship between size and apparent refractive index.

(Technical Reports 7, 28 (list I), Publication 20 (list II)). Subsequently, the reasons for the deviations of the measured refractive index from the true refractive index were also investigated in an expansion of earlier theoretical work by Zimm and Dandliker (J. Phys. Chem., 58, 644 (1954)).

The theoretical equation arrived at reproduced the empirical relation and was in agreement with the experimental data referred to above (Technical Report 20 (list I); Publications 7, 10 (list II)). It followed from this study that it is very risky to determine the refractive index of a particle or macromolecule of colloidal dimensions by conventional techniques if they scatter light very strongly even though one may use highly dilute systems.

### 8. Stabilization, Sensitization and Coagulation of Colloidal Systems by Macromolecular Additives

In connection with attempts to stabilize polystyrene latices used for the investigations described in Section AI, an extensive preliminary study was undertaken on the effect of macromolecules, in general, and of polyelectrolytes, in particular, as stabilizing or coagulating agents. Unexpectedly, the publications resulting from these investigations became the nucleus for a rapidly expanding special field of interest in the area of colloids, particularly after the late V. LaMer joined this field. The importance of those early results and of the large number of additional results obtained in the meantime by a large number of authors, in connection with the problem of water pollution, is now generally recognized. The results obtained within the framework of the present project were reported, beginning in 1954, in Technical Reports 6, 18, 37, 38 (list I) and Publications 5, 8, 34, 35, and 57 (list II).

### 9. Various Other Investigations

In the field of optics, an interesting investigation by the late A. F. Stevenson dealt with the Krishnan reciprocity theorem (Technical Report

30 (list I) which subsequently was published in the Journal of Chemical Physics. An investigation by the writer dealt with the performance of mixture rules used for the evaluation of the refractive index of a solute (Technical Report 57 (list I)) and with the application of the results for the purpose of determining optically the partial specific volume of a solute by means of interferometric measurements (Technical Report 59 (list I); Publications 56, 58 (list II)). To be mentioned from among miscellaneous non-optical investigations are (1) a simple, new differential technique for determining the density of dispersed colloidal materials (Technical Report 25 (list I) and Publication 19 (list II)) and (2) the development and application of a few new equations which allow one to increase the precision of data derived from viscosity measurements on polymer solutions (Technical Report 7a (list I)).

B. REPORTS AND PUBLICATIONS

TECHNICAL REPORTS SENT TO THE OFFICE OF NAVAL  
RESEARCH

(LIST I)

1. W. Heller and W.J. Pangonis, "Explicit Light Scattering Functions For Spherical Colloidal Particles", January 2, 1953, total pp. 106, ms. pp. 64.
2. W.J. Pangonis and W. Heller, "Tables of Scattering Functions For Spherical Colloidal Particles" ( $\lambda = 0.2(0.2)7.0$ ;  $n = 1.05(0.05)1.30$ ), May 1954, total pp. 52, ms. pp. 5.
3. W. Heller, "Tables of Scattering Functions For Spherical Colloidal Particles II" ( $\lambda = 8.0(1.0)15$ ;  $n = 1.15, 1.20, 1.25$ ), June 1954, total pp. 19, ms. pp. 5.
4. A.F. Stevenson, "The Determination of Spherical Particle Size Distribution From Turbidity Spectra", 1954, total pp. 7, ms. pp. 7.
5. W. Heller and W.J. Pangonis, I. "The Light Scattering of Spherical Colloidal Particles", and W. Heller, II. "The Determination of Particle Size and Refractive Index Near the Turbidity Maximum in Monodisperse Suspensions of Spherical Particles", June 30, 1954, total pp. 10, ms. pp. 7.
6. Thomas L. Fugh, "'Steric' Protection of Colloidal Particles I", July 1954, total pp. 49, ms. pp. 25.
7. Thomas L. Fugh, "The Refractive Index and Density of Polystyrene and Polyvinyl Toluene Latices", July 1954, total pp. 60, ms. pp. 41.
- 7a. W. Heller, "Treatment of Viscosity Data on Polymer Solutions", (Special Report No. 1), August 1, 1954, total pp. 46, ms. pp. 26.
8. W. Heller, Joseph N. Fnel, Richard M. Tabibian, and John M.L. Watson, I. "Experimental Verification of the Mie Theory of Light Scattering", and W. Heller, Thomas L. Fugh, II. "'Steric Protection' of Hydrophobic Colloidal Particles by Adsorption of Flexible Macromolecules", August 10, 1954, total pp. 10, ms. pp. 8.
9. W. Heller, "Tables of Scattering Functions For Spherical Colloidal Particles III" ( $\lambda = 8.0(1.0)15.0$ ;  $n = 1.05, 1.10, 1.30$ ), August 15, 1954, total pp. 13, intro. pp. 1.
10. Richard M. Tabibian, "Particle Size Determination of Spherical Colloidal Particles by Light Scattering I. The Specific Turbidity", August 20, 1954, total pp. 72, ms. pp. 36.

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11. W. Heller, A.F. Stevenson, "A. Theory of Light Scattering by Spheroids  
B. On Krishnan's Reciprocity Relation in Light Scattering", July 18, 1955,  
total pp. 20, ms. pp. 18.
12. A.F. Stevenson, "The Theory of the Determination of Size Distribution in  
Heterodisperse Systems by Light Scattering II", July 25, 1955, total pp. 8,  
ms. pp. 5.
13. William J. Pangonis and W. Heller, "Tables of Scattering Functions For  
Colloidal Particles" ( $\alpha = 0.2(0.2)7.0$ ;  $n = 1.5(0.05)1.30$ ), (appendix to  
Technical Report #2), August 1955, total pp. 31, intro. pp. 2.
14. Max Krolak and W. Heller, "Tables of Scattering Functions For Spherical  
Colloidal Particles" ( $\alpha = 0.2(0.2)1.3$ ;  $n = 1.05(0.05)1.30$ ), (2nd Appendix  
to Technical Report #2), September 1955, Total pp. 2, intro. pp. 1.
15. Richard H. Tabibian, "Particle Size Determination of Spherical Colloidal  
Particles by Light Scattering", II. The Specific Scattering at  $90^\circ$ ,  
September 1955, total pp. 27, ms. pp. 3.
16. W. Heller, "Tables of Scattering Functions For Spherical Colloidal Particles  
V." (I  $\alpha = 0.2(0.2)15.2$ ;  $n = 1.20$  II  $\alpha = 2(2)20$ ; 39, 40, 41;  $n = 1.05$   
III  $\alpha = 16(1)21$ ;  $n = 1.10$ ), January 1, 1956, total pp. 33, intro. 2.pp.
17. W. Heller, "Tables of Scattering Functions For Spherical Colloidal Particles  
VI.", May 1, 1956, total pp. 24, intro. pp. 3.
18. W. Heller and Thomas L. Fugh, "Stabilization and Coagulation of Colloidal  
Solutions with Polyelectrolytes", May 1956, Total pp. 1.
19. Richard H. Tabibian, W. Heller and Joseph H. Epol, "Experimental Inves-  
tigations on the Light Scattering of Colloidal Spheres", June 1956,  
total pp. 19, ms. pp. 17.
20. Masayuki Hasegaki and W. Heller, "Effect of Light Scattering Upon the  
Refractive Index of Dispersed Colloidal Spheres", September, 1956,  
total pp. 5.
21. W. Heller and W.J. Pangonis, "Theoretical Investigations of the Light  
Scattering of Colloidal Spheres. I. The Specific Turbidity", June 1, 1957,  
total pp. 9, ms. pp. 8.
22. W. Heller and Richard H. Tabibian, "Experimental Investigations of the  
Light Scattering of Colloidal Spheres. II. Sources of Error in Turbidity  
Measurements", June 5, 1957, total pp. 15, ms. pp. 13.
23. W. Heller, "Dityndallism, Conservative Dichroism and Anisotropy, from-  
ising Effects for the Determination of the shape of Colloidal Particles and  
Molecules", June 12, 1957, total pp. 28, ms. pp. 22.

24. Richard Tabibian and W. Heller, "Experimental Investigations on the Light Scattering of Colloidal Spheres. III. The Specific Scattering at  $90^\circ$ ", June 16, 1957, total pp. 32, ms. pp. 18.
25. Thomas L. Pugh and W. Heller, "Density of Polystyrene and Polyvinyltoluene Latex Particles", September 23, 1957, total pp. 8.
26. W. Heller, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. II. Accurate Interpolations of Theoretical Turbidity Data", September 25, 1957, total pp. 3, ms. pp. 2.
27. W. Heller, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. III. Analytical Expressions for Turbidity Approximating the Performance of the Mie Equations Prior to the First Maximum", September 27, 1957, total pp. 7.
28. W. Heller and T.L. Pugh, "Experimental Investigations on the Effect of Light Scattering Upon the Refractive Index on Colloidal Particles", October 1, 1957, total pp. 14.
29. W. Heller and H. James McCarty, "Theoretical Investigations on the Light Scattering of Colloidal Spheres IV. Specific Turbidity in the Lower Microscopic Range and Fine Structure Phenomena", February 15, 1958, total pp. 13, ms. pp. 4.
30. A.F. Stevenson, "Note on Krishnan's Reciprocity Relation in Light Scattering", February 20, 1958, total pp. 3.
- 30a. W. Heller, Masayuki Nakagaki and Morton L. Wallach, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. V. Forward Scattering", August 15, 1958, total pp. 21, ms. pp. 11.
31. M. Nakagaki and W. Heller, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. VI. Backward Scattering", August 20, 1958, total pp. 15, ms. pp. 8.
32. W. Heller and M. Nakagaki, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. VII. Dissymmetry in Unpolarized and Polarized Light", May 1, 1959, total pp. 31, ms. pp. 12.
33. M. Nakagaki and W. Heller, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. VIII. The Angular Location of Intensity Maxima in the Radiation Diagram of Colloidal Spheres", June 20, 1959, total pp. 28, ms. pp. 12.
34. Morton L. Wallach, "The Determination of Size Distribution Curves by Light Scattering and Related Investigations", August 1, 1959, total pp. 78, ms. pp. 42.



35. W. Heller and Richard Tabibian, "Experimental Investigations on the Light Scattering of Colloidal Spheres. IV. Scattering of Linearly Polarized Light and the 'Scattering Ratio' at an Angle of Observation of  $90^\circ$ ", February 1, 1960, total pp. 44, ms. pp. 28.
36. Morton L. Wallach, Marvin F. Walden and Rodney Ku, "Partial Tabulation of  $\zeta$ -Spectra For Determining Size Distribution Curves From Light Scattering", March 1, 1960, total pp. 21, ms. pp. 2.
37. Thomas L. Pugh and W. Heller, "Coagulation and Stabilization of Colloidal Solutions with Polyelectrolytes", June 1, 1960, total pp. 14, ms. pp. 12.
38. W. Heller and T.L. Pugh, "'Steric' Stabilization of Colloidal Solutions by Adsorption of Flexible Macromolecules", June 1960, total pp. 23, ms. pp. 17.
39. W. Heller and W. J. Pangonis and Nikolaos A. Economou, "Theoretical Investigations of the Light Scattering of Colloidal Spheres. X. The 'Scattering Ratio' and Depolarization of Light Scattering at an Angle of Observation of  $90^\circ$ ", June 1, 1960, total pp. 13.
40. W.J. Pangonis and W. Heller and Nikolaos A. Economou, "Theoretical Investigations of the Light Scattering of Colloidal Spheres. IX. Lateral Scattering at  $90^\circ$  from Incident Natural and Linearly Polarized Light", June 1, 1960, total pp. 39, ms. pp. 7.
41. K. Okano and E. Wada, "Theory of Light Scattering by Thin Rod-Like Macromolecules in a Liquid Subjected to Shear", August 1, 1960, total pp. 12, ms. pp. 9.
42. Arthur F. Stevenson, W. Heller and Morton L. Wallach, "Theoretical Investigations of the Light Scattering of Colloidal Spheres. XI. Determination of Size Distribution Curves from Spectra of the Scattering Ratio or from Depolarization Spectra", August 15, 1960, total pp. 25, ms. pp. 17.
43. Morton L. Wallach, W. Heller and Arthur F. Stevenson, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. XII. The Determination of Size Distribution Curves from Turbidity Spectra", August 30, 1960, total pp. 16, ms. pp. 6.
44. W. Heller, Riechi Wada and Louis A. Pazanian, "Macromolecular Shape From Light Scattering in Streaming Solutions", September 1, 1960, total pp. 5, ms. pp. 2.
45. W. Heller and Hari L. Sathnagar, "Theoretical Investigations on the Light Scattering of Spheres. XIII. The Wave Length Exponent of Differential Turbidity Spectra", July 31, 1961, total pp. 30, ms. pp. 14.
46. L.A. Pazanian, "Light Scattering of Flowing Colloidal Systems", August 31, 1961, total pp. 95, ms. pp. 82.



47. Rodney T. Ku, "Determination by Scattering Spectra of Particle Size Distribution Curves in Emulsions and Coagulating Latices", June 15, 1962, total pp. 104, ms. pp. 41.
48. Yuichi Ikeda, "Extension of the Rayleigh-Gans Theory for Spherical and Spheroidal Particles", October 15, 1962, total pp. 55, ms. pp. 39.
49. W. Heller, "Theoretical and Experimental Investigations on the Light Scattering of Colloidal Spheres", November 15, 1962, total pp. 43, ms. pp. 25.
50. W. Heller, H.L. Wallach and A.F. Stevenson, "Experimental Investigations on the Light Scattering of Colloidal Spheres. V. Determination of Size Distribution Curves By Means of Spectra of the Scattering Ratio", April 15, 1963, total pp. 23, ms. pp. 16.
51. Morton L. Wallach and W. Heller, "Experimental Investigations on the Light Scattering of Colloidal Spheres. VI. Determination of Size Distribution Curves by Means of Turbidity Spectra", June 25, 1963, total pp. 18, ms. pp. 10.
52. W. Heller and Morton L. Wallach, "Experimental Investigations on the Light Scattering of Colloidal Spheres. VII. Resolving Power of the  $\sigma$ -Spectra Method for Determining Size Distribution Curves", June 26, 1963, total ms. 8, ms. pp. 4.
53. Hari L. Ehatnagar and W. Heller, "Theoretical Investigations on the Light Scattering of Spheres. XIV. The Wave Length Exponent of Differential Scattering Spectra for an Angle of Observation of  $90^\circ$ ", August 10, 1963, total pp. 12, ms. pp. 6.
54. W. Heller, "Theoretical Investigations on the Light Scattering of Spheres. XV. The Wave Length Exponents at Small  $\alpha$ -Values", December 20, 1963, total pp. 17, ms. pp. 10.
55. W. Heller, "Theoretical Investigations on the Light Scattering of Spheres. XVI. Range of Practical Validity of the Rayleigh Theory", July 14, 1964, total pp. 24, ms. pp. 10.
56. W. Heller, "Range of Practical Validity of the Debye and the Rayleigh Equations for Determining Molecular Weights From Light Scattering and Methods Allowing a Limited Extension of This Range", July 21, 1964, total pp. 26, ms. pp. 14.
57. W. Heller, "Remarks on Refractive Index Mixture Rules", July 28, 1964, total pp. 15, ms. pp. 13.
58. W. Heller, "A Generalization of the Debye Light Scattering Equation", December 3, 1964, total pp. 4.

59. W. Heller, "Application of  $(dn/dc)$ -Data For The Determination Of Partial Specific Volumes, Free Solute And Bulk Volumina And Of Solute-Solute and Solute-Solvent Interactions", February 22, 1965, total pp. 32, ms. pp. 19.
60. B.M. Greene, "Determination of Particle Size Distributions in Emulsions by Light Scattering", November 15, 1965, total pp. 134, ms. pp. 46.
61. W. Heller, K. Yajnik, and J. Witeczek, "Application of Computer Facilities for the Determination of Size Distribution in Polymer Latices," February 1, 1967, total pp. 12, ms. pp. 7.
- 61a. Mukul Yajnik, Electronic Computations of Light scattering Functions for Heterodisperse Systems of Isotropic Spheres; July 6, 1967; total pp. 18, Ms. pp. 9.
62. Herbert J. Doppke and W. Heller, "Quantitative Dimensional Characterization of Nonspherical Objects from their Light Scattering in Streaming Systems." March 1, 1967. total pp. 15. Ms. pp. 6.
63. A. F. Stevenson; Light Scattering by Spheroidal Particles Oriented by Streaming;" May 20, 1968; total pp. 19; Ms. pp. 10.
64. N. Ahmad, W. Heller, and M. Nakagaki: "Light Scattering of Hydrodynamically Deformed Macromolecules;" July 10, 1969; total pp. 6; Ms. pp. 4.
65. W. Heller, R. Tabibian, M. Nakagaki, and L. Papazian; "Flow Light Scattering" July 20, 1969, total pp. 32; Ms. pp. 23.
66. W. Heller and J. Witeczek . "Experimental investigations on the Light Scattering of Colloidal Spheres; VIII. Determination of the Angular Variation of Light Scattering by Means of a New Type of Reflection free Scattering Cell." November 10, 1969; total pp. 20, Ms. pp 11.

II. Publications of Work Supported by the Office of Naval Research (LIST II)

Bracketted Number: Number in complete list of publications  
One Asterisk: \* Work not concerned with main topic but  
acknowledged as supported by ONR  
Two Asterisks: \*\* Book (one copy sent to ONR)

1. (66). W. Heller and W. J. Pangonis, "Solid Angle Corrections for Light Scattering Measurements," *Phys. Rev.*, 90, 345 (1953).
2. (67). W. Heller and W. J. Pangonis, "Refractive Index Corrections for Molecular Weight Determined from Light Scattering," *Phys. Rev.*, 90, 345 (1953).
3. (70). W. Heller and W. J. Pangonis, "Light Scattering of Spherical Colloidal Particles," *J. Chem. Physics*, 22, 948 (1954).
4. (71). W. Heller, J. N. Epel, and R. Tabibian. I., "Experimental Verification of the Mie Theory of Light Scattering," *J. Chem. Phys.*, 22, 1777 (1954).
5. (72)\*. W. Heller and T. L. Pugh, "'Steric Protection' of Hydrophobic Colloidal Particles by Adsorption of Flexible Macromolecules," *J. Chem. Phys.*, 22, 1778 (1954).
6. (73). W. Heller, "The Determination of Particle Size and Refractive Index Near the Turbidity Maximum in Monodisperse Suspensions of Spherical Particles", *J. Chem. Phys.*, 23, 342 (1955).
7. (74). W. Heller and M. Nakagaki, "Effect of Light Scattering Upon the Apparent Refractive Index Of Dispersed Polymers," *Bull. Am. Phys. Soc.*, Series 2, I, 123 (1956).
8. (75)\*. W. Heller and T. L. Pugh, "Stabilization and Coagulation of Colloidal Solutions with Polyelectrolytes," *J. Chem. Phys.*, 24, 1107, (1956).
9. (76). R. Tabibian, W. Heller, and J. N. Epel, "Experimental Investigations on the Light Scattering of Colloidal Spheres. I. The Specific Turbidity," *J. Coll. Sci.*, 11, 195 (1956).
10. (77). M. Nakagaki and W. Heller, "Effect of Light Scattering Upon the Refractive Index of Dispersed Colloidal Spheres," *J. Applied Phys.*, 27, 975 (1956).
11. (78). W. Heller, "Dityndallism and Bidissymetry and Their Prospective Usefulness in Colloid and Polymer Research," *Bull. Am. Phys. Soc.*, II, 2, 149 (1957).

12. (79). A. Peterlin, W. Heller, and M. Nakagaki, "Theory of Flow Bidissymetry of Light Scattering by Flexible Macromolecules," *Bull. Am. Phys. Soc.*, II, 2, 149 (1957).
13. (80). W. Heller and M. Nakagaki, "Theory of Flow Dityndallism of Flexible Macromolecules," *Bull. Am. Phys. Soc.*, II, 2, 149 (1957).
14. (81). W. Heller and R. Tabibian, "Experimental Investigations on the Light Scattering of Colloidal Spheres. II. Sources of Error in Turbidity Measurements," *J. Colloid Sci.*, 12, 25 (1957).
15. (82). W. Heller and W. J. Pangonis, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. I. The Specific Turbidity," *J. Chem. Phys.* 26, 498 (1957).
16. (83). W. Heller, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. II. Accurate Interpolations of Theoretical Turbidity-Data," *J. Chem. Phys.*, 26, 920 (1957).
17. (84). W. Heller, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. III. Analytical Expressions for Turbidity Approximating the Performance of the Mie Equations Prior to the First Maximum." *J. Chem. Phys.* 26, 1258 (1957).
18. (85). \*\* W. J. Pangonis, W. Heller, and A. Jacobson, "Tables of Light Scattering Functions for Spherical Particles," Wayne State University Press, 1957 (116 pp.)
19. (86). \* W. Heller and T. L. Pugh, "Density of Polystyrene and Polyvinyltoluene Latex Particles," *J. Colloid Sci.*, 12, 173 (1957).
20. (87). \* W. Heller and T. L. Pugh, "Experimental Investigations on the Effect of Light Scattering Upon the Refractive Index of Colloidal Particles." *J. Colloid Sci.*, 12, 294 (1957).
21. (88). R. M. Tabibian and W. Heller, "Experimental Investigations on the Light Scattering of Colloidal Spheres. III. The Specific Scattering at 90°," *J. Colloid Sci.*, 13, 6, (1958).
22. (90). A. Peterlin, W. Heller, and M. Nakagaki, "Light Scattering and Statistical Shape of Streaming Freely Flexible Linear Macromolecules," *J. Chem. Phys.* 28, 470 (1958).
23. (91). W. Heller and H. James McCarty, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. IV. Specific Turbidities in the Lower Microscopic Range and Fine Structure Phenomena," *J. Chem. Phys.*, 29, 78 (1958).

24. (93). W. Heller, M. Nakagaki, and M. L. Wallach, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. V. Forward Scattering," J. Chem. Phys., 30, 444 (1959).
25. (94). M. Nakagaki, and W. Heller, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. VI. Backward Scattering", J. Chem. Phys., 30, 783 (1959).
26. (95). W. Heller, "The Determination of Particle Sizes and Size Distributions by Means of Light Scattering;" "Analytical Chemistry in Nuclear Reactor Technology;" Oak Ridge Natl. Lab. TID - 7568 (Pt. 3) 3 (1959).
27. (96). M. Nakagaki and W. Heller, "Anisotropic Light Scattering by Flowing Flexible Macromolecules," J. Polymer Sci., 38, 117 (1959).
28. (98). W. Heller, "Anisotropic Light Scattering of Streaming Suspensions and Solutions," Reviews of Modern Physics 31, 1072 (1959).
29. (99). W. Heller and M. Nakagaki, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. VII, Dissymmetry in Unpolarized and Polarized Light," J. Chem. Phys., 31, 1188 (1959).
30. (101). M. Nakagaki and W. Heller, "Visibility of Luminous Objects Through Fog in Absence and Presence of Search Lights," Bull. Am. Phys. Soc., 5, 28 (1960).
31. (102). W. Heller, R. M. Tabibian, T. L. Pugh, M. Nakagaki, E. Wada, and L. Papazian, "Apparatus for Determining the Shape of Macromolecules from Anisotropic Light Scattering and Preliminary Experimental Results," Bull. Am. Phys. Soc, 5, 173 (1960).
32. (103). M. Nakagaki and W. Heller, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. VIII. The Angular Location of Intensity Maxima and Minima in the Radiation Diagram of Colloidal Spheres," J. Chem. Phys., 32, 835, (1960).
33. (104). \*\* W. J. Pangonis and W. Heller, "Angular Scattering Functions for Spherical Particles" Wayne State University Press, 1960 (222pp.)
34. (107). \* W. Heller and T. L. Pugh, "'Steric' Stabilization of Colloidal Solutions by Adsorption of Flexible Macromolecules," J. Polymer Sci. 47, 203 (1960).

35. (108). \* T. L. Pugh and W. Heller, "Coagulation and Stabilization of Colloidal Solutions with Polyelectrolytes," J. Polymer Sci. 47, 219 (1960).
36. (109). W. Heller, E. Wada, and L. A. Papazian, "Macromolecular Shape from Light Scattering in Streaming Solutions," J. Polymer Sci., 47, 481 (1960).
37. (110). W. J. Pangonis, W. Heller, and N. A. Economou, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. IX. Lateral Scattering at  $90^\circ$ , from Incident Natural and Linearly Polarized Light," J. Chem. Phys. 34, 960 (1961).
38. (111). W. Heller, W. J. Pangonis, and N. A. Economou, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. X. 'Scattering Ratio' and Depolarization of Light Scattered at an Angle of Observation of  $90^\circ$ ." J. Chem. Phys., 34, 971 (1961).
39. (112). \*\* A. F. Stevenson and W. Heller, Table of Scattering Functions for Heterodisperse Systems, Wayne State University Press. 1961 (214pp.)
40. (113). A. F. Stevenson, W. Heller, and M. L. Wallach, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. XI. Determination of Size Distribution Curves from Spectra of the Scattering Ratio or from Depolarization Spectra." J. Chem. Phys. . 34, 1789 (1961).
41. (114). M. L. Wallach, W. Heller, and A. F. Stevenson, "Theoretical Investigations on the Light Scattering of Colloidal Spheres. XII. The Determination of Size Distribution Curves from Turbidity Spectra " J. Chem. Phys., 34, 1796 (1961).
42. (117). W. Heller, H. L. Bhatnagar, and Masayuki Nakagaki, "Theoretical Investigations on the Light Scattering of Spheres. XIII. The 'Wavelength Exponent' of Differential Turbidity Spectra," J. Chem. Phys., 36, 1163 (1962).
43. (119). W. Heller and R. Tabibian, "Experimental Investigations on the Light Scattering of Colloidal Spheres. IV. The Scattering Ratio," J. Phys. Chem. , 66, 2059 (1962).
44. (121). W. Heller, "Radiation Scattering: Yesterday's Cinderella, Today's Primadonna," Naval Research Reviews, 16, 1 (1963).
45. (122). W. Heller, "Theoretical and Experimental Investigations of the Light Scattering of Colloidal Spheres;" "Proceedings of the Interdisciplinary Conference on Electromagnetic Scattering." Ed. M. Kerker; Pergamon Press, New York, NY (1963) p. 101.

46. (123). W. Heller and M. L. Wallach, "Experimental Investigations on the Light Scattering of Spheres. V. Determination of Size Distribution Curves by Means of Spectra of the Scattering Ratio," *J. Phys. Chem.*, 67, 2577 (1963).
47. (124). H. L. Bhatnagar and W. Heller, "Theoretical Investigations on the Light Scattering of Spheres. XIV. The Wave Length Exponent of Differential Scattering Spectra for an Angle of Observation of  $90^\circ$ " *J. Chem. Phys.*, 40, 480 (1964).
48. (125). M. L. Wallach and W. Heller, "Experimental Investigations on the Light Scattering of Colloidal Spheres. VI. Determination of Size Distribution Curves by Means of Turbidity Spectra," *J. Phys. Chem.* 68, 924 (1964).
49. (126). W. Heller and M. L. Wallach, "Experimental Investigations on the Light Scattering of Colloidal Spheres. VII. Resolving Power of the sigma-spectra Method for Determining Size Distribution Curves," *J. Phys. Chem.*, 68 931 (1964).
50. (127). W. Heller, "Theoretical Investigations on the Light Scattering of Spheres. XV. The Wavelength Exponents at Small  $\alpha$ -Values," *J. Chem. Phys.*, 40, 2700 (1964).
51. (130). W. Heller, "Elements of the Theory of Light Scattering. I. Scattering in Gases, Liquids, Solutions, and Dispersions of Small Particles," in: Light Scattering from Dilute Polymer Solutions; Ed. D. McIntyre and F. Gornick, National Bureau of Standards, Gordon and Breach Science Publishers (1964).
52. (131). W. Heller, "Theoretical Investigations on the Light Scattering of Spheres. XVI. Range of Practical Validity of the Rayleigh Theory." *J. Chem. Phys.*, 42, 1609 (1965).
53. (133). W. Heller, "A Generalization of the Debye Light Scattering Equation," *J. Polymer Sci.*, A3, 2367 (1965).
54. (134). W. Heller, "Range of Practical Validity of the Debye and the Rayleigh Equations for Determining Molecular Weights from Light Scattering and Methods Allowing a Limited Extension of this Range," *J. Polymer Sci.*, A3, 3313 (1965).
55. (135). \*\* H. Denman, W. J. Pangonis, and W. Heller, "Angular Scattering Functions for Spheres." Wayne State University Press, 1966 (294pp.)
56. (136). W. Heller, "Application of  $(dn/dc)$ -Data for the Determination of Partial Specific Volumes of Dissolved Macromolecules" *J. Polymer Sci.*, A2 4, 209 (1966).

57. (139). \* W. Heller, "Effects of Macromolecular Compounds in Disperse Systems; Pure and Applied Chemistry, 12, 249 (1966).
58. (140). W. Heller, "Application of  $\{dn/dc\}$ -Data for the Determination of Partial Specific Volumes," Rubber Chemistry and Technology, 40, 1281 (1967).
59. (141). H. L. Doppke and W. Heller, "Quantitative Dimensional Characterization of Nonspherical Objects from their Light Scattering in Streaming Systems," J. Colloid and Interface Sci., 25, 586 (1967).
60. (142). H. L. Doppke and W. Heller, "A new optical method for determining the dimensions of nonspherical scattering objects," published in "Characterization of Macromolecular Structure," publication 1573 National Academy of Sciences, 68 (1968).
61. (143). M. Yajnik, J. Witeczek, and W. Heller, "Electronic Computations of Light Scattering Functions for Heterodisperse Systems of Isotropic Spheres," J. Polymer Sci., 25, 99 (1968).
62. (144). W. Heller, "Analytical Value of Light Scattering Measurements in Streaming Systems," Applied Polymer Symposia 8, 206. (1969).
63. (145). \*\* M. Yajnik, W. Heller, and J. Witeczek, "Tables of Angular Light Scattering Functions for Heterodisperse Systems," 1301 pages, Wayne State University Press, December 1969.
64. (146). N. Ahmad, W. Heller, and M. Nakagaki, "Light Scattering of Hydrodynamically Deformed Macromolecules," J. Colloid and Interface Sci., 31, 585 (1969).
65. (148). W. Heller, R. Tabibian, M. Nakagaki, and L. Papazian, "Flow Light Scattering I. Theoretical Principles of the Effect and Apparatus for its Measurement," J. Chem. Phys., 52, 4294 (1970).
66. (150). W. Heller and J. Witeczek, "Experimental Investigations on the Light Scattering of Colloidal Spheres VIII. Brief Survey of Problems in Angular Light Scattering Measurements and Performance of a New Type of Reflection Free Scattering Cell," J. Phys. Chem. 74, 4241 (1970).
67. (154). \*\* W. Heller, G. Langolf, and M. Nakagaki, Light Scattering Functions for Nonspherical Particles, 130 pages. Wayne State University Press, Wayne State University, Detroit (1972)

III. LIST OF PLANNED FURTHER PUBLICATIONS ON COMPLETED OR PARTIALLY COMPLETED ONR-SPONSORED RESEARCH (LIST III)

1. J. Witczek and W. Heller, "Experimental Investigations on the Light Scattering of Colloidal Spheres IX. Combination of Spectral and Angular Variation of Light Scattering for the Determination of Size Distribution Curves in Heterodisperse Systems", J. Phys. Chem.
2. W. Heller and B. Greene, "Experimental Investigations on the Light Scattering of Colloidal Spheres X. Size Distributions in Emulsions and their Variation with Experimental Conditions", J. Phys. Chem.
3. W. Heller and W. Bergmann, "Theoretical Investigations on the Light Scattering of Spheres XVII. Quantitative Analysis of Very Heterodisperse Systems by Means of ADLS (Angular Dispersion of Light Scattering Spectra)", J. Chem. Phys.
4. M. Nakagaki, W. Heller and N. Ahmad, "Flow Light Scattering II. Study of Macromolecular Deformation in Laminar Flow", J. Chem. Phys.
5. W. Heller and H. Doppke, "Flow Light Scattering III. Dimensional Analysis of Rigid Non-spherical Objects from Flow Light Scattering", J. Chem. Phys.
6. H. Doppke and W. Heller, "Flow Light Scattering, a Sensitive Effect for Detecting and Evaluating Turbulent Flow and its Inhibition by Suitable Additives", J. Rheology.
7. W. Heller and M. Nakagaki, "Theoretical Investigations on the Light Scattering of Spheroids I. A Generalization of the Rayleigh-Gans-Stevenson Theory on the Light Scattering of Spheroids", J. Chem. Phys.
8. M. Nakagaki and W. Heller, "Theoretical Investigations on the Light Scattering of Spheroids II. Dissymmetry and Depolarization of Light Scattering by Spheroids", J. Chem. Phys.
9. W. Heller and M. Nakagaki, "Flow Light Scattering IV. Depolarization of Light Scattering by Spheroids in Flow", J. Chem. Phys.
10. M. Nakagaki and W. Heller, "Recalculation by Modern Computational Methods of the Peterlin-Stuart Functions Needed for the Evaluation of Streaming Birefringence", J. Optical Soc. Am.

11. M. Nakagaki, G. Langolf and W. Heller, "Light Scattering Functions for Non-spherical Particles in Flow", Wayne State University Press.
12. W. Heller and G. Langolf, "Depolarization of Light Scattered by Spheroids", Wayne State University Press.
13. M. Nakagaki and W. Heller, "Theoretical Investigations on the Light Scattering of Spheres XVIII. The Angular Location of Intensity Maxima and Minima in the Radiation Diagram of Colloidal Spheres, Part 2", J. Chem. Phys.
14. W. Bergmann and W. Heller, "Theoretical Investigations on the Light Scattering of Spheres XIX. The Effect of Heterodispersion upon the Angular Location of Intensity Maxima and Minima in the Radiation Diagram of Spheres", J. Chem. Phys.
15. M. Nakagaki and W. Heller, "Spectral Variation of Light and Radar Transmittancy through Fog as a Function of Average Water Droplet Size", J. Opt. Soc. Am.
16. W. Heller, "Simultaneous Determination of Particle Size and Refractive Index from Light Scattering", J. Chem. Phys.

**NOTE:** The names of the periodicals are tentative and subject to change. A footnote in back of the projected publications will acknowledge the support received from the Office of Naval Research. One copy of the manuscript will be mailed to the Office of Naval Research in Washington, D. C., a second to the ONR Office at Ann Arbor, and a third to the Regional Office in Chicago, Illinois.

C. Ph. D. DEGREES GRANTED FOR WORK  
SPONSORED BY THE OFFICE OF NAVAL RESEARCH

<u>Name</u>	<u>Degree Granted In</u>	<u>Present Association</u>
W. J. Pangonis	1952	Experimental Station DuPont Corporation Wilmington, Delaware
R. M. Tabibian	1955	Same
T. L. Pugh	1956	Same
M. L. Wallach	1959	Same
L. A. Papazian	1961	Mobil Oil Co.
R. T. Wu	1962	Texus Company
B. W. Greene	1965	Research Associate Dow Chemical Midland
J. P. Witczek	1969	American Cyanamid
H. J. Doppke	1969	Civil Service, State of Indiana
N. Ahmad	1969	Professor of Chemistry University of Peshawar Pakistan

**D. POSTDOCTORAL STUDENTS (S) AND VISITING PROFESSORS (P)  
ASSOCIATED WITH THE PROJECT ON HALF-TIME (H) OR FULL TIME (F)**

<u>Name</u>	<u>Present Association</u>	<u>Years on Project</u>	<u>Period</u>	<u>Status within Project</u>
W. J. Pangonis	Research Associate DuPont, Wilmington, Delaware	1*	1952-53	S (F)
A. F. Stevenson	Professor, Mathematics Department, Wayne State University	1**	1953-54	P (H)
H. Bhatnagar	Professor, Kurukshetra University, Kurukshetra, India	1 1/4	1957-58	S (F)
A. Peterlin	Director, Camille Dreyfus Laboratory, Research Triangle Institute, Durham, N. C.	1	1955-56	P (F)
M. Nakagaki	Professor, Kyoto University, Kyoto, Japan	2	1956-58	P (F)
E. Wada	Professor, Faculty of Science and Engineering, Nippon University Tokyo, Japan	2	1958-60	P (F)
A. Peterlin	see above	1/4	1960	P (H)
Y. Ikeda	Senior Scientist, Fuji Spinning Company, Tokyo, Japan	2	1960-62	S (F)
T. Handa	Professor, Chemistry Dept Science University, Tokyo	1 1/2	1962-64	P (F)
M. Yajnik	Regional Manager, Textile Industries, Madras, India	3	1965-68	S (F)
M. Nakagaki	see above	1	1968-69	P (F)

\*Spent several years before 1952 on the respective work as a predoctoral student.  
\*\* Was, in addition, an active consultant to the project until 1968.

E. OTHER COLLABORATORS MENTIONED IN LISTS BI, BII OR BIII

Dr. H. B. Denman, Professor of Physics, Wayne State University, wrote the program and supervised the computations of the light scattering functions in Publication 55 in list II. Professor Denman did this work on a fully complimentary basis.

Mr. G. Langolf, as an undergraduate student in the College of Engineering at Wayne State University (formerly a programmer for Uniroyal and now a graduate student at the University of Michigan, Ann Arbor) wrote the computer program for the light scattering functions used in Publication 67 of list II. Mr. Langolf used the compensation received toward his tuition expenses and other expenses associated with his education. Mr. Langolf will also be the co-author of two further publications (11 and 12 in list III).

Mr. Vern Bergmann, at present a graduate student in the Chemistry Department at Wayne and working on light scattering with the Ph. D. degree as the objective, made important contributions to the final, revised program that led to the book listed as Publication 63 in list II. He will also be co-author of two publications (13 and 14 in list III).

Mr. N. Economou aided, on a part-time basis during summer vacation, with manual computations incorporated in Publications 37 and 38 of list II. Mr. Economou, at that time a graduate student in the Chemistry Department, is now a professor at the University of Salonika, Greece.