FINAL REPORT

ANALYSIS OF LUNAR SURFACES

NASA Grant NsG-127-61

Submitted to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D. C.

by

Anthony Turkevich

Enrico Fermi Institute for Nuclear Studies
University of Chicago
Chicago, Illinois

May 1966

ANALYSIS OF LUNAR SURFACES
(Final Report)

NASA Grant NsG-127-61

Anthony Turkevich

Enrico Fermi Institute for Nuclear Studies
University of Chicago
Chicago, Illinois

I. INTRODUCTION

This Final Report on Grant NsG-127-61, of the United States National Aeronautics and Space Administration, covers the technical work performed mostly during the period February 1961 through July 1965, although some activities, including report preparation, have continued through April 1966.

The research on this grant was a basic scientific investigation of a method of chemical analysis of lunar and planetary material by use of alpha particles and the development of analytical procedures for an alpha-scattering experiment on a suitable lunar vehicle.

The method of alpha scattering is a new technique of chemical analysis. Its potential applications on instrumented space missions were pointed out by Turkevich[1,2] in 1960 and 1961. The grant covering the work of this report was made on the basis of a proposal by Turkevich[1] to the National Aeronautics and Space Administration in 1960 and extended on the basis of a proposal[4] submitted by Turkevich in 1962.

with the Argonne National Laboratory, and with the Jet Propulsion
Laboratory. The instrument development work and Surveyor mission-
oriented activities have been supported by subcontracts with the
Jet Propulsion Laboratory (JPL-NASA #950315 and JPL-NASA #950750).

Although it would have been desirable to have a more dis-
tinct separation of the fundamental studies from the instrument
and mission-oriented work, this was not possible in this program.
It must be remembered that the original Surveyor Lunar Mission
payload was already established in 1961, and that the potentiali-
ties of the technique of Alpha Scattering had to be demonstrated
in both theoretical and practical ways to merit consideration for
inclusion as a Surveyor experiment. It must also be remembered
that the Surveyor mission requirements, as well as target dates,
have changed drastically during the period of this work. The
progress in fundamental understanding of the technique, as well as
normal technological advances, have been fed into the instrument
development and mission planning as much as possible. In return,
many of the fundamental measurements have been carried out using
instruments designed with specific mission requirements in mind.
As a result, the reports on this new method of analysis reflect
both basic considerations and practical aspects of the program.

The following reports contain information on the work
performed under this grant:

1. The original proposal[1] for a grant made to NASA by
    Anthony Turkevich (1960).

2. An article[2] in the Journal, _Science_, by Anthony
    Turkevich (1961).

3. A report[3] to NASA by Anthony Turkevich covering the work on the original grant (1961).

4. A proposal[4] for an extension of the NASA grant made by Anthony Turkevich (1962).

5. An article in the Journal of Geophysical Research[5] (1965), in collaboration with James H. Patterson and Ernest Franzgrote.

6. A report[6] by Anthony Turkevich on the work performed under the grant (1966).

7. A preprint[7] of a paper to be submitted to the Review of Scientific Instruments describing the instrument planned for Surveyor (1966), in collaboration with Karlfried Knolle, Richard E. Emmert, Wayne A. Anderson, James H. Patterson, and Ernest Franzgrote.

8. A preprint[8] of a paper to be submitted to the Journal of Geophysical Research describing the Surveyor Chemical Analysis Experiment and presenting the results of rock analyses with the Alpha-Scattering Instrument (1966), in collaboration with Karlfried Knolle, Ernest Franzgrote, and James H. Patterson.

The reports 1-6 inclusive have already been submitted; preprints 7 and 8 are being made part of this report.

This Final Report will not repeat the detailed presentations given in these reprints and preprints but will point out the results accomplished under this grant, referring to the more complete reports where necessary.

II. RESULTS OF FUNDAMENTAL STUDIES

The objectives of this part of the work were to establish the characteristics and usefulness of the interactions of alpha particles with matter as a method of chemical analysis. The results will be discussed in the following categories, although the division is, in many cases, rather arbitrary:

A. the scattering of alpha particles,

B. the protons produced by alpha particles,

C. the role of ionization energy loss by charged particles in interpreting the spectra of scattered alpha particles and protons,

D. the interpretation of complex spectra in terms of chemical composition.

Topics A, B, and C are covered in some detail in published reference 6. Experimental data relative to topic D are to be found in the preprint, reference 8.

A. The Scattering of Alpha Particles

At the energies available from alpha radioactive sources, the principal scattering mode from all elements is elastic scattering. In the case of elements heavier than silicon, the elastic scattering is predominantly Rutherford coulomb scattering; for light elements, such as carbon, oxygen, and fluorine, nuclear

resonance scattering is the dominant mode; for intermediate elements, both processes contribute. In all cases, the conservation laws determine the maximum energy with which alpha particles can be scattered at a given angle. This maximum energy is a monotonic function of the mass number.

The spectra of alpha particles scattered from a thick target (thicker than a few microns) is continuous, with a high-energy maximum determined by these conservation laws. During the course of this program,[2,5,7,8] such spectra have been obtained for more than thirty elements, many under several geometrical situations.

The nature of the spectra from elements for which Coulomb scattering is the dominant mode is understood semiquantitatively in terms of the Rutherford scattering cross section and the ionization energy loss cross sections of the particular element.[5] The spectral features are relatively independent of angle and differ, from element to element, primarily in the high-energy endpoints. Under the best conditions (source monochromaticity, geometry, and detector and electronics stability), most elements up to nickel can be resolved. For light elements, such as magnesium, the isotopic complexity can be detected. For elements heavier than nickel, the sensitivity of the technique increases, but the resolution between elements of comparable mass number soon deteriorates.

The spectrum of scattered alpha particles from a light element often shows distinctive structure, reflecting the basic resonance nature of the fundamental nuclear scattering process. This is important from the standpoint of chemical analysis because this structure provides more information concerning the element responsible for the scattering than is present in the position of the high-energy endpoint of the spectrum. Together with the enhanced probability of scattering because of these nuclear effects, the result is a significantly enhanced sensitivity of the technique for light elements than was originally anticipated. For other than space applications, an understanding of these nuclear resonance interactions makes possible a prediction of instrument parameters (energy of alpha particles, angles of scattering) which would enhance the sensitivity for particular elements.

On the other hand, although the scattering from light elements can be qualitatively understood on this basis, the prediction of detailed spectrum shapes from fundamental data is too hard to be practical. The nuclear interaction cross sections are not only strongly energy dependent, but the scattered alpha particles have strong angular characteristics. The result is that the response of a particular instrument to each light element ($Z \leq 20$) must be established empirically. This is in contrast to the case for heavy elements, the spectra of which can all be predicted from the shapes of a few.

The relative sensitivity of the elastic backscattering of alpha particles as a method of chemical analysis for different elements has been established and is summarized in Fig. 13 of reference 5. For elements heavier than calcium, the sensitivity increases approximately as $Z^{3/2}$. The sensitivity is high, but very energy dependent, for light elements such as carbon and oxygen. It is a minimum in the region Z = 11-20.

The absolute sensitivity of this technique has also been established. This, of course, depends on the geometry of a particular instrument and on the source strength employed. Even under the most favorable conditions, this is not a very rapid method of analysis. If the sample to be examined is of controlled geometry — for example, a relatively smooth plate — an instrument can be designed to give a relatively complete analysis in a few hours. In the case of samples of unknown characteristics, such as material on the moon or Mars, the optimum instrument parameters are such as to require of the order of one day for a good analysis.

Similarly, the technique does not lend itself particularly to the examination of small areas of samples. In the instruments investigated, typical samples ranged from a few to almost a hundred square centimeters in size.

Because the range of alpha particles from radioactive sources is only a few microns in condensed materials, this technique analyzes only the top surface of a sample. The disadvantage of this is, of course, that the surface may not be representative of the bulk of the material. This characteristic is an

advantage, however, if the object is actually to study the
surfaces of materials. In the present work, experimental data
relevant to this point have been obtained on organic films on
metals and on the oxidation of aluminum.

B. Protons from (α, p) Reactions

Because of the minimum in probability of alpha back-
scattering for elements with atomic numbers between ten and
twenty, the protons produced by (α, p) reactions in these ele-
ments are an important aspect of the technique of analysis with
alpha particles. This modification was an early development of
the work under this grant. The intensities of protons are usually
much lower than those of scattered alpha particles, but, using
special detectors, the latter can be removed without significantly
affecting the spectra of the former.

The spectra of protons from (α, p) reactions in thick
samples of all the light elements have been determined,[2,5,7,8]
using the various instruments developed during the course of this
work. For rock analyses, this mode of operation is particularly
useful because several geochemically important elements, such as
sodium and aluminum, are usually not very abundant and would
otherwise be very hard to determine with the desired accuracy,
using alpha particles alone. In other applications, this should
be a very effective technique for analyzing surfaces coated with
fluorine compounds.

C. The Role of Ionization Energy Loss
by Charged Particles

The quantitative interpretation of the scattered alpha and proton spectra from complex materials depends on the ionization energy loss (stopping power) of charged particles in different materials. The fundamental theory is treated in reference 5, and it is shown that semi-empirical methods are adequate for moderate precision. However, for the highest precision and in special situations, the role of ionization energy loss should be treated more exactly. In particular, cases where hydrogen may be present in significant amounts may require special attention.

D. The Interpretation of Complex Spectra
in Terms of Chemical Composition

Aside from the role of ionization energy loss (see section II.C.), the main problem in interpreting the scattered alpha and proton spectra obtained from a complex sample in terms of the chemical composition is a calculational one. A computer is given a library of spectra representing the response of an instrument to pure elements and asked what combination represents the observed spectrum from a sample of unknown composition.

Although several calculational techniques have been tried for doing this, the straightforward least-squares procedure seems adequate. The only refinement has been the introduction of four extra variables which allow the computer to decide if a fit to the observed data can be obtained by adjusting the zero offset

-11-

and the gain of the instrument (in both proton and alpha modes
independently) from those nominally given by the calibration.
In practice, these calculated instrument shifts have always been
small and have made very little difference in the results.

Reference 8 gives the results of the analysis of eight
rocks by this technique and the comparison with the values
obtained by conventional analyses. For thirteen elements
(carbon, oxygen, fluorine, sodium, magnesium, aluminum, silicon,
"calcium," "iron," and "barium"), the agreement between the two
types of analyses range from 0.3 to 2.1 atomic per cent. This
range of precision appears adequate to differentiate between
the major classes of rocks that might be expected on the lunar
surface.

III. SUMMARY OF CONTRIBUTIONS TO INSTRUMENT DEVELOPMENT AND MISSION PLANNING

As indicated in the Introduction, the fundamental work
has been closely related to the instrument development and mis-
sion planning. References 5 and 6 give information on the
instruments developed during the course of this program. Refer-
ence 7 describes in some detail the instrument developed for
Surveyor. As mentioned in the Introduction, many of these
instruments were used to obtain the data for the fundamental
studies on this new method of analysis.

Likewise, mission planning has had to proceed in parallel
with the basic investigations. The present plan for a Scientific
Surveyor experiment to determine the chemical composition of the

lunar surface by the techniques described in this report is summarized in reference 8.

IV. PROSPECTS FOR THE FUTURE

The work under this grant has concentrated on the fundamental characteristics of the technique but has been slanted toward imminent use on the Surveyor Lunar Mission. It is appropriate, however, to note the possibilities of other applications and further developments of this technique of analysis. Three relatively obvious ones are listed here:

A. The technique — and even the instruments already developed for Surveyor — seem ideally suited for some other projected Space Missions. Two examples are:

1. Use on Apollo missions, either as an aid in selecting samples to be brought back, or as instruments to perform analyses of interesting regions while astronauts are resting, or to telemeter the information back to earth after astronaut departure. Such instruments could analyze the lunar material under local conditions. It is not at all clear that a lunar sample brought back, even with the greatest precautions, will properly represent, in all respects, the state of matter on the moon.

2. To analyze the surface of Mars. A proposal has already been submitted[9] by Turkevich for an experiment on Voyager. An experiment to analyze the atmosphere of Mars, using the principles of the technique developed on this grant, has been proposed by Franzgrote.[10]

B. The technique appears to be particularly suitable for studying surfaces and chemical reactions at surfaces. Protective coatings on materials could be studied and perhaps controlled by use of this method. Only very preliminary work has been done in this area.

C. The analytical instrument could be made more versatile and precise by incorporating an X-ray mode of operation. The alpha particles, besides being scattered and inducing (α,p) reactions, also produce X-rays in the materials exposed. Recent detector developments[11] indicate that this mode could be incorporated into a space instrument. The prospect would be to provide good resolution between neighboring elements heavier than iron and increased sensitivity, particularly for geochemically important elements, such as potassium.

V. PERSONNEL ASSOCIATED WITH THE RESEARCH
UNDER THIS GRANT

At various times, the following personnel at the
University of Chicago have participated in the work performed
under this grant.

    A.   Post Ph.D. Fellow: Dr. Karlfried Knolle[†]

    B.   Students: Mr. Andrew Beretvas
                    Mr. Anastasios Katsanos
                    Capt. James Phillips
                    Mr. Ken Sowinski
                    Dr. Andreas Van Ginneken

    C.   Technical Personnel: Mr. Edwin Blume
                              Mr. Warren Geiger
                              Mr. Bernard Wendring

VI. ACKNOWLEDGMENTS

In addition to the personnel directly associated with
the research under this grant, the author acknowledges the helpful
cooperation of the Laboratory for Astrophysics and Space Research
of the Enrico Fermi Institute for Nuclear Studies (formerly
Chicago Midway Laboratories) led by Mr. James E. Lamport. The
author likewise is indebted to his colleagues at the Enrico Fermi
Institute for Nuclear Studies, notably the late S. K. Allison and
to Professors John Simpson, Herbert L. Anderson, and Nathan
Sugarman for much helpful consultation.

[†] Present address: Tulpenhofstrasse 29, Offenbach Am Main,
Germany.

VII. REFERENCES

[1] Turkevich, A., "Proposal for Chemical Analysis of Material on the Moon and Planets Using Rutherford Scattering of Charged Particles." Submitted to the National Aeronautics and Space Administration, 13 September 1960.

[2] Turkevich, A., "Chemical Analysis of Surfaces by Use of Large-Angle Scattering of Heavy Charged Particles," Science $\underline{134}$, 672 (1961).

[3] Turkevich, A., Report on National Aeronautics and Space Administration Grant NsG-127-61, 10 July 1961.

[4] Turkevich, A., "Chemical Analysis of Lunar Surface Material Using Alpha Particle Bombardment II." Submitted to the National Aeronautics and Space Administration, 29 November 1962.

[5] Patterson, J. H., Turkevich, A., and Franzgrote, E., "Chemical Analysis of Surfaces Using Alpha Particles," J. Geophys. Res. $\underline{70}$, 1311 (1965).

[6] Turkevich, A., Report on National Aeronautics and Space Administration Grant NsG-127-61, February 1966.

[7] Turkevich, A., Knolle, K., Emmert, R. E., Anderson, W. A., Patterson, J. H., and Franzgrote, E., "An Instrument for Lunar Surface Chemical Analysis," May 1966. Preprint included with this report. To be submitted to Rev. Sci. Instr.

[8] Turkevich, A. L., Knolle, K., Franzgrote, E., and Patterson, J. H., "The Chemical Analysis Experiment for the Surveyor Lunar Mission," May 1966. Preprint included with this report. To be submitted to J. Geophys. Res.

[9] Turkevich, A., "Preliminary Proposal for a Scientific Experiment on the 1969-1971 Voyager Missions to Mars." Submitted to the National Aeronautics and Space Administration, 12 August 1965.

[10] Franzgrote, E. J., Marshall, J. H., Patterson, J. H., and Turkevich, A. L., "Analysis of the Martian Atmosphere by Alpha-Particle Bombardment - The Rutherford Experiment" (Preliminary Submittal). Submitted to the National Aeronautics and Space Administration, 2 August 1965; see, also, Marshall, J. H. and Franzgrote, E. J., "Analysis of the Martian Atmosphere by Alpha-Particle Bombardment - The Rutherford Experiment," JPL Space Program Summary #37-26, Vol. IV, pp. 148-154 (1963).

[11] A. Metzger, of the Jet Propulsion Laboratory, and E. K. Hyde, of the Lawrence Radiation Laboratory of the University of California, have called my attention to these possibilities.