DETERMINATION OF
NEUTRON CAPTURE CROSS SECTIONS
AND
RESONANCE PARAMETERS
FOR
VANADIUM AND THE ISOTOPES OF TELLURIUM

MASTER

Progress Report
for Period June 1, 1975-November 30, 1975

R. R. Winters

Denison University
Granville, Ohio 43023

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

December 1975

Prepared for
The U.S. Energy Research and Development Administration

Under Contract No. E(11-1)-2696

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed or represents that its use would not infringe privately owned rights.

DENISON UNIVERSITY

Abstract

Analysis of $^{51}\text{V}(n,\gamma)$ data taken at the forty-meter flight station at the Oak Ridge Electron Accelerator has been essentially completed over the neutron energy (laboratory) range 2.5-100 keV. Resonance parameters for some seventy-five resonances have been extracted. In particular, radiative widths not previously measured have been obtained for many resonances above 50 keV. Data analysis will be continued at least up to neutron energy 150 keV before a paper, already in preparation, will be submitted for publication.

As part of our continuing study of mass-dependent behavior of resonance parameters, a continuing interest in the astrophysical applications of (n,γ) cross sections, and as a test of recent modifications to our analysis computer codes, data analysis (begun before the initiation of this contract) of $^{205}\text{Tl}(n,\gamma)$ and $^{205}\text{Tl}(n,x)$ data was continued. This work is now essentially completed over the neutron energy range 2.5-100 keV. Extremely interesting departures from predictions of the statistical model for the resonance parameters have been observed. We are energetically engaged in efforts to finish this very exciting aspect of our work. A letter to Physical Review Letters is presently in preparation. A paper¹⁾ discussing the astrophysical significance of the $\text{Tl}(n,\gamma)$ reactions has been submitted for publication. That paper is included with this report.

After considerable effort, the principal investigator has concluded that the Denison computer system is not adequate for certain aspects of the required data analysis. Alternate approaches to enable data analysis to be done during the academic year at Denison are being considered.

The analysis of the $\text{Te}(n,\gamma)$ data is barely underway and will be the primary focus of the principal investigator's efforts over the coming year. However, the tellurium (n,γ) data (for mass numbers 122, 124, 125, 126, 128 and 130) have been processed from the time-of-flight form to effective cross section and a normalization to a recent natural tellurium (n,γ) measurement has been completed.

DENISON UNIVERSITY

Progress Report

Data analysis of both $V(n,\gamma)$ and $Tl(n,\gamma)$ and $Tl(n,x)$ data proceeded very smoothly during the summer 1975 and continues to go well (although at a slower pace) during the present academic semester.

$V(n,\gamma)$

Approximately seventy-five resonances in $^{51}V(n,\gamma)$ have been analyzed using the Busing-Levy non-linear least squares fitting program as modified by R. L. Macklin. A paper reporting the results of this analysis is in preparation, but will not be submitted for publication until the analysis has been completed to 150 keV incident neutron energy. The analysis completed thus far yields, in addition to individual resonance parameters, an average radiative width $\langle\Gamma_\gamma\rangle = (728 \pm 120)$ meV and an average resonance spacing (without regard to total spin and parity J^π) $\langle D \rangle = (1.71 \pm 0.12)$ keV. The average spacing and strength function calculated for sixteen s-wave resonances below 100 keV is $D_0 = (5.01 \pm 0.64)$ and $S_0 = (7.50 \pm 2.57)$ (in 10^{-4} units). The p-wave average spacing and strength function calculated for the eighteen known p-wave resonances below 100 keV is $D_1 = (3.02 \pm 0.44)$ keV and $S_1 = (0.22 \pm 0.12)$ (10^{-4} units). The quantities S_0 and S_1 are of particular importance in the calculation of average cross sections using the optical model formalism. These average cross sections are often utilized in estimating the effects due to the neutron flux in reactors or thermonuclear devices. However, because the interior of both a reactor and a contained plasma fusion device can be described by a characteristic temperature, it would appear that a Maxwellian-averaged capture cross section should be of importance to the design and operation of such devices. Hence, the Maxwellian-averaged cross sections for $V(n,\gamma)$ have been calculated over a range of temperatures expected to be encountered in the plasma containment thermonuclear devices and in the core of fast breeder reactors. It is hoped that such averaged cross sections, obtained using the excellent energy resolution available at ORELA, will prove useful in our search for better energy sources.

$Te(n,\gamma)$

When the analysis of the $Te(n,\gamma)$ data was started, it became clear that there was a significant screening effect by the lucite binder material in the Te_2O_3 samples. The computer codes in use in the beginning of the analysis had to be modified to account for this effect. Rather than begin the analysis of a series of some six isotopes of tellurium, it was decided to first use the newly modified fitting codes on a continuing problem, the $^{205}Tl(n,\gamma)$ reaction. The thallium sample was an oxide with lucite binder and, hence, offered the opportunity to check the modified computer codes without the inevitable ambiguities arising from isotopic misidentification in the tellurium data.

DENISON UNIVERSITY

However, some progress in the analysis of the $\text{Te}(n,\gamma)$ data has been accomplished. The data has been processed from the preliminary time-of-flight form to effective cross section. The normalization of the effective cross section for each isotope was accomplished using a recently run natural tellurium sample. This latter measurement was carried out with very careful attention to the detection efficiency normalization relative to the 4.9 ev gold resonance. We are confident that the cross section normalization has been accomplished to an accuracy of better than 5 per cent.

$\text{Tl}(n,\gamma)$ and $\text{Tl}(n,x)$

By the initial date of this contract, ^{205}Tl had already shown itself to be an extremely interesting nucleus²¹, meriting study in terms of possible violations of predictions made by the statistical and valency nuclear models.

Approximately 33 per cent of the effort of the principal investigator have been devoted to the analysis of the $^{205}\text{Tl}(n,\gamma)$ and $^{205}\text{Tl}(n,x)$ data. This effort has been greatly aided by the collaboration of J.A. Harvey (ORNL), R.L. Macklin (ORNL), and D. Earle (Canadian AEC). Harvey had measured the total cross section spectrum for $^{205}\text{Tl}(n,x)$ for three sample thicknesses in the neutron energy range of interest to the (n,γ) work. He generously provided this data to the principal investigator for analysis. Hence, both the (n,γ) and (n,x) data were available for the extraction of resonance parameters. This meant that, in approximately one hundred resonances, both $g\Gamma_n$ and $g\Gamma_\gamma$ could be extracted from the data, and in many cases, the statistical spin factor, g , could also be determined. Hence, one of the most careful spectroscopic studies of a high mass nucleus ever possible is nearing completion.

The results have been surprising. It now seems clear that there are at least two clearly resolvable classes of resonances in the $^{205}\text{Tl}(n,\gamma)$ reaction, one class with average radiative width $\langle\Gamma_\gamma\rangle \approx 0.135$ ev and the other class with $\langle\Gamma_\gamma\rangle \approx 1.5$ ev. The average radiative widths differing by a factor of 10. More significantly, there seems to be a very strong correlation between the spin and parity, J^π , of the resonances and $\langle\Gamma_\gamma\rangle$, with the s-wave resonances having the larger $\langle\Gamma_\gamma\rangle$. Such an effect might, at first thought, be ascribed to a single-particle effect in the compound nucleus, but this does not seem to be the case. The valency model (a model of nuclear decay which assumes a strong single-particle nature of the nuclear states) predicts that the radiative widths Γ_γ and neutron widths Γ_n should be strongly correlated. We find no statistically significant correlation. A letter to Physical Review Letters is in preparation reporting the essence of our study of the $^{205}\text{Tl}(n,\gamma)$ reaction. A more nearly complete discussion of the data with a table of resonance parameters will be in a paper presently being prepared for submission to Physical Review.

DENISON UNIVERSITY

Excitement continued to center around the $^{205}\text{Tl}(n,\gamma)$ reaction as a result of a paper by Blake and Schramm³⁾ published in the late spring, 1975. This paper stressed the cosmological importance of better cross section determinations for $^{203}\text{Tl}(n,\gamma)$ and $^{205}\text{Tl}(n,\gamma)$. Macklin and the principal investigator have responded to this request and have submitted a paper¹⁾ "Stellar Neutron Capture in the Stable Thallium Isotopes," to the Astrophysical Journal. A preprint of that paper is included with this report.

The Denison pdp 11/45 Computer System

The happy sense of achievement over the work during these past six months was tempered slightly by the negative results stemming from an attempt to alter the (n,γ) analysis computer codes written for the IMB 360, so that they could be run on the Denison pdp 11/45. After a month of considerable effort, it is now clear that, given the system configuration available at Denison, the analysis cannot be readily accomplished at Denison.

The difficulty is essentially one of machine use priority. The Denison system is a time-share system using the computer language BASIC. Unfortunately (at least for one interested in performing non-trivial computation), the BASIC interpreter is relatively unsophisticated. The object module produced by the interpreter is apparently much less efficient than, say, an object module produced by the FORTRAN compiler on the same system. One example of the impracticability of performing the analysis on the Denison computer system should suffice to make the point. In performing the non-linear least squares fit to the Doppler broadened Breit-Wigner resonance shape, it is necessary to evaluate the real part of the complex error function. Because the pdp 11/45 does not support complex arithmetic, a series representation of the error function was used in the computation. Approximately fifty terms in the series are usually adequate for the precision required by the fitting codes. However, even after a good deal of effort to maximize the efficiency of the computational algorithm, the calculation consumed about ten minutes of cpu time. This calculation must be done approximately 2500 times for each fit, and hence, the use of the pdp 11/45 seems impractical. The principal investigator is now considering using a time-share facility available commercially in nearby Columbus, Ohio.

¹⁾ Macklin, R.L. and Winters, R.R. submitted to Astrophys. J.

²⁾ Earle, E.D. and Winters, R.R., Bull. Am. Phys. Soc., April (1974)

³⁾ Blake, J.B. and Schramm, D.N., Astrophys. J. 197, 615 (1975)

UNIVERSITY-TYPE CONTRACTOR'S RECOMMENDATION FOR
DISPOSITION OF SCIENTIFIC AND TECHNICAL DOCUMENT

(See Instructions on Reverse Side)

1. AEC REPORT NO. C00-2696-001	2. TITLE Determination of Neutron Capture Cross Sections and Resonance Parameters for Vanadium and the Isotopes of Tellurium
---------------------------------------	---

3. TYPE OF DOCUMENT (Check one):

- ☒ a. Scientific and technical report
☐ b. Conference paper:

Title of conference _____

Date of conference _____

Exact location of conference _____

Sponsoring organization _____

- ☐ c. Other (Specify) _____

4. RECOMMENDED ANNOUNCEMENT AND DISTRIBUTION (Check one):

- ☒ a. AEC's normal announcement and distribution procedures may be followed.
☐ b. Make available only within AEC and to AEC contractors and other U.S. Government agencies and their contractors.

5. REASON FOR RECOMMENDED RESTRICTIONS:

6. SUBMITTED BY: NAME AND POSITION (Please print or type)

Dr. Ron R. Winters
Associate Professor
Department of Physics

Organization

Denison University
Granville, Ohio 43023

Signature

Ron Winters

Date

December 5, 1975

FOR AEC USE ONLY

7. AEC CONTRACT ADMINISTRATOR'S COMMENTS, IF ANY, ON ABOVE ANNOUNCEMENT AND DISTRIBUTION RECOMMENDATION:

8. PATENT CLEARANCE:

- ☐ a. AEC patent clearance has been granted by responsible AEC patent group.
☐ b. Report has been sent to responsible AEC patent group for clearance.
☐ c. Patent clearance not required.