MASTER

THE MEASUREMENT AND ANALYSIS
OF NEUTRON CROSS SECTIONS WITH
THE OAK RIDGE LINEAR ACCELERATOR
NEUTRON FACILITY

Progress Report
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Abstract

The research work conducted under the USDOE Contract Ey-76-S-02-2439.A003 involved the measurement, analysis and interpretation of high resolution neutron total and capture cross sections in the neutron energy range of few eV to few hundred keV with many nuclei.

The extensive measurements of total and capture cross section in many nuclei: ^{64}Zn , ^{66}Zn , ^{67}Zn , ^{68}Zn , ^{70}Zn , ^{57}Fe , ^{58}Fe have been analyzed using a R-matrix multi-level multi-channel code for the total cross section and LSFIT code for the capture cross sections. The results of these analyses have been reported at many APS Meetings, International Symposium and have been submitted for publications to the Physical Review. The main interest in making these measurements in some of these nuclei was the investigation of statistical properties of complex spectra, the determination of the s- and p-wave strength functions, level densities, radiative widths and the parameters of the optical model potential used for the interaction of neutrons with nuclei.

The measurements of total and capture cross section in nuclei also provide valuable data for nucleosynthesis of elements, and a better understanding of the neutron interaction with nuclei. The later information is obtained via investigation of the level resonance parameters and their statistical averages such as the level spacing for given angular momentum and spin, Γ_n and Γ_γ and strength function. The systematics of resonance levels such as spin and parity and their dependence on strength function,

level density etc., are also important. The capture cross section measurements are also complementary to the measurements of neutron total cross sections.

These measurements in certain nuclei are equally important for their application in the reactor design. The measurements in the separated isotopes of iron, zinc and chromium were undertaken to obtain more precise values of the above mentioned quantities, than is available at present.

The high resolution total cross section measurements in yttrium nucleus were undertaken in order to locate the intermediate states as has been predicted by the theorists. The analysis of these data had been completed up to 250 keV and the analysis had been extended up to about 500 keV to locate the intermediate states for s- and p-wave neutron interaction.

During this period some effort was also spent in modifying various computer programs of data transfer, area and shape analysis of neutron total cross sections data, LSFIT code for capture area analysis and the MULTI program for the R-matrix analysis of total cross section data.

The detailed accomplishment of the research work is given in the following pages.

1(a) High resolution neutron resonance spectroscopy in ^{64}Zn - I

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High resolution neutron total cross-section measurements on the separated isotope ^{64}Zn have been made in energy range of few eV to about 500 keV using a pulsed neutron time-of-flight technique with a nominal resolution of 0.07 ns/m. We have analyzed the cross section data up to 370 keV using a multi-level multi-channel computer code and obtained the values of resonance parameters (E_0 , J^π , $g r_n$). From these results we obtain the following values for the average properties of resonance parameters: $\langle D \rangle_{l=0} = (3.59 \pm 0.16)$ keV, $S_0 (\times 10^4) = (1.89 \pm 0.26)$ and $S_1 (\times 10^4) = (0.59 \pm 0.06)$. We have also investigated the neutron width and nearest neighbor spacing distributions for 103 s-wave resonances up to 370 keV. The neutron width distribution follows a chi-squared distribution with $\nu = (1.15 \pm 0.30)$. We have determined values for Dyson-Mehta's Δ_3 statistic for s-wave levels up to 300 keV as a function of energy. These are found to be in excellent agreement with the predicted values as explained in Table V. Similarly the linear coefficient of correlation between nearest neighbor spacings gives a value of $\rho = -0.35$ in agreement with the predicted value of the random matrix model. The value for the mean p-wave level spacing is larger than expected from the $(2J+1)$ density law, indicative of missed p-wave levels.

NUCLEAR REACTIONS: $^{64}\text{Zn}(n,n)$, $E = \text{few eV to } \sim 500 \text{ keV}$. Measured σ_t vs. E_n , deduced resonance parameters: Resonance energies E_λ , J^π , r_n^0 , r_n^1 , S_0 , S_1 , $\langle D \rangle_{l=0}$, $\langle D \rangle_{l=1}$.

TABLE IV. Neutron energy resolution and minimum value of $g\Gamma_n$ for which an asymmetrical shape due to $\lambda = 0$ can definitely be observed.

Neutron Energy E_n (keV)	Minimum Value of Γ_n (eV)	Present Reso- lution ΔE (eV)
20	0.3	18
40	1.0	37
60	2	56
80	3	80
100	4	100
140	5	150
170	6	190
200	7	230
250	8	305
300	9	380
350	12	475

TABLE V. The average level spacing, Δ_3 value and the correlation coefficient values for the nearest neighbor spacings for s-wave resonances as a function of E_n . The last column gives the theoretical value of Δ_3 . The lower part of the table excludes the 4 resonances marked with asterisks in Table II.

Energy Range (keV)	No. of Reso- nances	Average level spacings $\langle D \rangle$ (keV)	Corre- lation coeffi- cient	Δ_3 exp.	Δ_3 Theory
0-100	28	(3.57±0.35)	-0.40	0.36	0.33
0-200	56	(3.57±0.25)	-0.41	0.34	0.40
0-250	70	(3.57±0.22)	-0.38	0.35	0.42
0-300	83	(3.62±0.21)	-0.35	0.36	0.44
0-100	27	(3.70±0.37)	-0.49	0.52	0.33
0-200	52	(3.85±0.28)	-0.48	0.60	0.40
0-250	66	(3.79±0.24)	-0.46	0.53	0.42
0-300	79	(3.80±0.22)	-0.43	0.77	0.44

1(b)High Resolution Neutron Capture Cross Sections In ^{64}Zn

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Total neutron capture cross section measurements in the separated isotope of $^{64}_{30}\text{Zn}$ have been made in the energy interval of 2.5-600 keV. These were made using time-of-flight techniques and a total energy γ -ray detector system with a nominal resolution of about 0.12 ns/m. Resonance energies and capture areas were determined for 194 resonances up to 130 keV. Values of the radiation widths and neutron widths for many resonances have been determined making use of the results available from transmission measurements. From these results a mean value of $\langle\Gamma_{\gamma}\rangle = (813 \pm 77)$ meV for s-wave and $\langle\Gamma_{\gamma}\rangle = (357 \pm 31)$ meV for p-wave resonances have been determined.

A value for the p-wave strength function $S_1 = (0.77 \pm 0.07) \times 10^{-4} \text{ ev}^{-1/2}$ was obtained for neutron energy up to 130 keV. The Bayes theorem for conditional probability was used to identify d-wave levels and from these resonances a value for d-wave strength function $S_2 = (0.5 \pm 0.1) \times 10^{-4} \text{ ev}^{-1/2}$ was obtained. The values for the p-wave mean level spacings for all resonances observed upto 130 keV and after eliminating d-wave resonances were (0.68 ± 0.04) and (0.98 ± 0.07) keV respectively. An analysis of the linear correlation coefficient between Γ_n^0 and Γ_{γ} gave a value of $p = (0.47 \pm 0.08)$ at a confidence level of 99.7%.

1(c) Statistical Properties of Complex States of ^{67}Zn
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High resolution neutron total and capture cross section measurements have been made on the separated isotope of ^{66}Zn in the energy range of few keV to about 1 MeV using the neutron time-of-flight technique and the pulsed Oak Ridge Electron Linear Accelerator. The nominal resolution of the measurements was 0.07 ns/m. The total cross section data has been analyzed up to 380 keV using a multi-level R-matrix code and the capture data up to 130 keV using the LSFIT code. From these analyses we have obtained the values of resonance parameters such as E_0 , $g\Gamma_n$, Γ_γ and values of average quantities $D_{\ell=0} = (4.62 \pm 0.30)$ keV, $D_{\ell=1} = (1.17 \pm 0.08)$ keV, $S_0 = 2.06 \pm 0.36$, $S_1 = 0.66 \pm 0.06$ and $S_2 = (0.60 \pm 0.09)$ in units of $10^{-4} \text{eV}^{-1/2}$. The values of total radiative widths are $(\Gamma_\gamma)_s = (0.45 \pm 0.10) \text{eV}$, $(\Gamma_\gamma)_p = (0.19 \pm 0.03) \text{eV}$.

The distribution of neutron reduced widths and level spacings of s- and p-wave resonances show excellent agreement with the Porter-Thomas and Wigner distributions respectively. The value of Δ_3 statistic for the ordering of s-wave energy levels is found to be in excellent agreement with the theoretical prediction of Dyson and Mehta.

A value of 0.59 ± 0.10 has been determined for the linear coefficient of correlation between neutron reduced width and radiative width of 26 s-wave resonances. This value is highly significant and has a confidence level of 99.7%.

1(d) Total Cross Section in Separated Isotopes of Zn
J.B. Garg, V.K. Tikku(SUNYA) and J.A. Harvey(ORNL)

The analysis of the total neutron cross section data in the isotopes of zinc with $A=67, 68$ and 70 has also been completed using the R-matrix MULTI program. The properties of resonance parameters ($E_\lambda, g\Gamma_n, J^\pi$) up to the energy of 380 keV have been investigated in the light of statistical theories and important information about their behavior has been obtained from these results. Several research papers containing these results are in preparation and will be shortly submitted for publication in the scientific journals.

1(e) Neutron Capture Cross Section of Zn Isotopes
J.B. Garg, V. Tikku (SUNYA) and J. Halperin and R.L. Macklin (ORNL)

Neutron capture cross section measurements in other separated isotopes of Zn ($A=67$ and 68), carried out at the ORELA time-of-flight facility over the energy interval of 2.6 to 600 keV have also been analyzed. Using the values of Γ_n determined from the complementary measurements of neutron total cross section in these nuclei, we have been able to determine the values of Γ_γ for most of the resonances. For very narrow resonances, whose Γ_n values could not be obtained from the transmission measurements, the assumed average value of Γ_γ was used to determine its neutron widths. From these strength function values for p-wave resonances have been obtained. A correlation analysis between Γ_γ and neutron widths has also been performed for these nuclei. Research papers containing these results are in preparation.

1(f) Neutron Total Cross Section In ^{57}Fe
J.B. Garg(SUNYA) and J.A. Harvey (ORNL)

The total neutron cross section in the separated isotope of ^{57}Fe (enriched to 99%), measured up to 500 keV using ORELA facilities has been analyzed using MULTI program and a paper describing these results is in preparation.

1(g) Neutron Total Cross Section in Isotopes of Chromium
J.B. Garg, V. Tikku (SUNYA) and J.A. Harvey (ORNL)

The total neutron cross section in the separated isotopes of chromium ($A=50, 52$), performed with ORELA neutron time-of-flight facility at 78.2 meter station, are being analyzed with the R-matrix multi-level multi-channel code and preliminary results of these analyses is in progress. The remaining analysis of these data will also be completed during the contract period.

OPTICAL MODEL POTENTIAL AND NEUTRON STRENGTH FUNCTIONS

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One of the most important quantities obtained from the measurements of high resolution neutron total cross sections in nuclei are the neutron strength functions and their variation with mass number. This quantity which is directly related to the nature of neutron interaction with the nucleus by a complex optical model potential can be given by the relation $\langle \Gamma_{nJ}^{\ell} \rangle / \langle D_{\ell J} \rangle$, where $\langle \Gamma_{nJ}^{\ell} \rangle$ is the mean value of neutron reduced widths of resonances of same ℓ and J . $\langle D_{\ell J} \rangle$ is the corresponding mean value of the level spacing. In the past few years many precise values of S_0 and S_1 in the mass region of $40 < A < 70$ have been obtained by Garg et al.¹⁻⁵ and others⁶) using high resolution neutron spectroscopy.

An optical model code consisting of a Woods-Saxon real volume potential (V) and a derivative Woods-Saxon imaginary potential (W_D) and a conventional real spin-orbit potential (V_S) was used to calculate these strength functions. The results of these calculations for $E_{lab} = 0.1$ MeV and the experimental results obtained from measurements in the energy range 0 to 300 keV are shown in figure 1(a) and (b) for S_0 and S_1 respectively. There appears to be a very good agreement with most of the nuclei.

Moreover, the same parameters with the following energy dependence of the real and imaginary potentials :
 $V = V_0 - 0.3 E_n$, $W_D = W_{D0} + 0.4 E_n$
 where E_n is in MeV, gave an excellent fit to the measured total cross section data⁶) in zinc in the energy range of 0.1 to 10 MeV. It seems thus apparent that a single set of optical model parameters can describe the neutron interaction in the medium mass region of nuclei over a wide energy range. The effect of isospin term ($N-Z/A$) on strength function values was also investigated.

Fig. 1

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Contract Requirement

The principal investigator has fully complied with the proposed research plans outlined in his proposal. He has spent about 20% of his time on this project during the academic year and 100% time for the two and a half summer months. He would continue to devote 20% of his time during the remainder of the contract period. A visiting scientist has spent 25% of his time on this project for four months and 100% of full time for the eight months on this project.

The principal investigator was on sabbatical leave from SUNY at Albany during the spring semester. He spent this time at the Centre d'etudes Nucleaires at Bruyere-le-chatel Paris, France. During his stay at this center he participated in the measurements of MeV neutron capture in few nuclei in collaboration with Dr. Grenier and his group. Moreover he also devoted some of his time to the preparation of manuscripts of papers reporting the results of cross section measurements on zinc isotopes. These papers have now been submitted to the Physical Review for publication.

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