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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.A004 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.

Neutron Widths And Level Spacings Of $^{64}\text{Zn}+n$ J.B. Garg and V.K. Tikku
SUNYA

and

J.A. Harvey
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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 370 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 multilevel multichannel computer code and obtained values of the resonance parameters $(E_0, J^\pi, g\Gamma_n)$. From these results we obtain the following values for the average properties of the resonance parameters: $\langle D \rangle_{l=0} = (3.59 \pm 0.16)$ keV, $S_0 (X 10^4) = 1.89 \pm 0.26$, and $S_1 (X 10^4) = 0.59 \pm 0.06$. 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 $p = -0.35$ 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.

Neutron Capture Cross Section in ^{64}Zn J.B. Garg and V.K. Tikku
SUNYA

and

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Total neutron capture cross section measurements of the separated isotope of $^{64}_{30}\text{Zn}$ have been made in the energy interval of 2.5-900 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 191 resonances up to 131 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 mean values of $\langle\Gamma_{\gamma}\rangle=(726\pm60)$ meV for s-wave and $\langle\Gamma_{\gamma}\rangle=(272\pm30)$ meV for p-wave resonances have been determined. A value for the p-wave strength function $S_1=(0.75\pm0.08)\times 10^{-4}\text{eV}^{-1/2}$ was obtained for neutron energy up to 130 keV. Bayes' theorem for conditional probability was used to identify d-wave levels and from these resonances a lower limiting value for d-wave strength function $S_2=(0.78\pm0.12)\times 10^{-4}\text{eV}^{-1/2}$ was obtained. The values for the p-wave mean level spacing for all resonances observed up to 130 keV, and after elimination of d-wave resonances, were found to be (0.68 ± 0.04) and $(1.10\pm0.07)\text{keV}$, respectively. An analysis of the linear correlation coefficient (ρ) between Γ_n^0 and Γ_{γ} gave a value of (0.47 ± 0.08) at a confidence level of 99.7%.

Statistical properties of complex states of $^{67}_{30}\text{Zn}$

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(Phys. Rev. Nov. 1981)

High resolution neutron total and capture cross section measurements have been made on the separated isotope ^{66}Zn in the energy range from a few keV to about 1 MeV using the neutron time-of-flight technique and the pulsed Oak Ridge Electron Linear Accelerator (ORELA). The nominal resolution of the measurements was 0.07 ns/m. The total cross section data have been analyzed up to 380 keV using a multi-level R-matrix formalism and the capture data up to 130 keV using a least squares fit program. From these analyses we have obtained the values of the resonance parameters E_0 , $g\Gamma_n$, and 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 $S_2 = (0.50 \pm 0.12)$ in units of $10^{-4} \text{ eV}^{-1/2}$. The values of average radiation widths are (0.39 ± 0.06) eV for s-wave resonances and (0.190 ± 0.013) eV for p-wave resonances. The distributions of neutron reduced widths and of level spacings of s- and p-wave resonances show excellent agreement with the Porter-Thomas and Wigner distributions respectively. The value of the Δ_3 statistic for the long range correlation 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 for the

correlation between the neutron reduced widths and the radiation widths of 26 s-wave resonances. This value is highly significant and has a confidence level of 99.7%.

NUCLEAR REACTIONS: $^{66}\text{Zn}(n,n)$, $^{66}\text{Zn}(n,\gamma)$, $E = \text{few keV to } \sim 380 \text{ keV}$. Measured total and capture cross sections vs neutron energy, deduced resonance parameters, E_0 , J^π , $g\Gamma_n$, Γ_γ , S_0 , S_1 , S_2 , D_0 , D_1 .

Neutron resonances in $^{70}_{30}\text{Zn}+n$

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Parameters (E_0 , $g\Gamma_n$, J^π , etc.) of the resonances observed in the neutron induced reaction on $^{70}_{30}\text{Zn}$ have been determined from 10 keV to about 400 keV using the pulsed neutron time-of-flight spectroscopy at ORELA with a neutron burst width of 5 ns and a nominal resolution of 0.07 ns/m at the highest energy. From these results we have obtained the values of average parameters such as $S_0 = (.51 \pm 0.28)$ and $S_1 = (0.90 \pm 0.10)$ in units of 10^{-4} , $D_0 = (6.82 \pm 0.53)$ and $D_1 = (2.42 \pm 0.23)$ in keV.

Furthermore the experimental data on the distribution of nearest neighbor level spacings and neutron reduced widths are in agreement with the Wigner and Porter-Thomas distributions, respectively. Excellent agreement with the Δ_3 statistic of Dyson and Mehta has been observed.

NUCLEAR REACTIONS: $^{70}\text{Zn}(n,n)$ up to $E_n \sim 400$ keV. Measured total cross section vs E_n , deduced resonance parameters E_0 , $g\Gamma_n$, J^π , S_0 , S_1 , D_0 and D_1 .

Coupled-Channels Calculation of $^{18}\text{O}+n$ Particle-Vibration
Doorway Resonances

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and

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The coupled-channels formalism is employed to study the $^{18}\text{O}+n$ particle-vibration doorway resonances in an attempt to explain the observed neutron resonance structure. Particle-vibration interaction is used to couple the neutron particle states to the 2^+ and 3^- target excited states. Proper Woods-Saxon well with spin-orbit term is used to describe the bound and scattering neutron wave functions. The particle-vibration coupling parameters β_2 and β_3 are taken from the charged particle inelastic scattering experimental results. Both positive and negative parity resonances are predicted below 2.0 MeV neutron energy. Effects of including the other target excited states in the coupled-channels calculations are in progress. The predicted doorway resonance reduced widths will be compared to the experimental results.

Particle-Vibration Doorway States in ($^{54}\text{Fe}+n$) System

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and

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The s- and p-wave resonances observed in the ($^{54}\text{Fe}+n$) reaction have been analyzed using a multilevel R-matrix code and values of $g\Gamma_n$ for the resonances have been determined. Strength functions have been obtained by averaging over a given energy interval using a Lorentzian weighting function as given by MacDonald¹. The experimental data display three doorway states. Calculations of the energies and widths of these doorway states from 2p-1h and particle vibration models² are consistent with the data. A detailed discussion of these results will be presented.

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Neutron Strength Functions and Particle-Vibration
Doorway States in Zinc Isotopes

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J.A. Harvey and R.L. Macklin, Oak Ridge National Lab.,

and

M. Divadeenam, Brookhaven National Lab.

R-matrix analysis of high resolution neutron total cross section data for the zinc isotopes has provided values for E_0 and $g\Gamma_n$ for the s- and p-wave resonances. From these results we have obtained the strength function for each partial wave by averaging the neutron reduced widths over energy intervals of 30 to 60 keV using a Lorentzian weighting function as given by MacDonald¹. Intermediate structure is observed in the ($^{66}\text{Zn}+n$), ($^{68}\text{Zn}+n$) and ($^{70}\text{Zn}+n$) systems. Values of E_d , $\Gamma_d^\downarrow$ and $\Gamma_d^\uparrow$ of the doorway states are obtained for each case. Particle-vibration doorway state calculations² were performed to obtain theoretical values of these quantities. A comparison of the experimental and calculated values will be presented.

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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.

Contract Requirement

The principal investigator has fully complied with the proposed research plans outlined in his proposal. He has spent about 30% 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 30% of his time during the remainder of the contract period. A visiting scientist has spent 100% of his time on this project full time for the whole year.

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