STATISTICAL PROPERTIES OF THE S-WAVE RESONANCES OF $^{235}$U

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Abstract

The resonance parameters of $^{235}$U in the energy range 0 eV to 2.25 keV were obtained from a generalized least squares analysis of a large set of experimental data using the Reich-Moore formalism in the fitting code SAMMY. The aim of the present paper is to present the statistical properties of the s-wave resonance parameters generated from this study.

Introduction

The first exhaustive work on the resonance parameters of $^{235}$U was the one of Michaudon et al. who obtained a value of 0.53 eV for the level spacing of the mixed s-wave resonances by adding 20% of small non-observed resonances to the observed set of levels. This was accomplished by the examination of the distribution of the spacings and of the neutron width of the resonances identified in the energy range 0 to 50 eV in high resolution transmission data taken with samples cooled to the liquid nitrogen temperature. At this time, it was concluded that nothing better could be obtained by using improved resolution in current transmission or fission cross section measurements.

Large improvement was obtained by Keyworth et al. and by Moore et al. from the analysis of experimental fission data taken with a polarized neutron beam and polarized $^{235}$U target. Analysis of spin-separated fission cross sections allowed the identification of more resonances due to a much smaller effect of the resonance overlapping. In the energy range up to 62 eV, Moore et al. identified 126 resonances compared to 92 resonances identified by Michaudon et al. By using a missing level estimator method they concluded that small resonances were still missing and the value of the average level spacing of the mixed s-wave resonances should be $(0.44 \pm 0.04)$ eV.

In the evaluation of the resonance parameters performed at ORNL, the spin-separated fission data were also used to identify the resonances in the energy range up to 100 eV, in conjunction with the SAMMY fits. In the energy range from 100 eV to 500 eV, the $\Delta_\gamma$-statistic method of Dyson and Metha was used to estimate the energy of an increasing number of missed resonances. In this energy range, the set of resonance parameters is not unique but has approximately the same statistical properties as those in the low energy range. Above 500 eV, the average spacing of the resonances used to fit the experimental data varies from 0.55 eV at 500 eV to about 1.0 eV at 2 keV. In this energy range, the resonance parameters give an accurate representation of the experimental data, in conjunction with the experimental resolution and temperature. Only the energy range 0 to 100 eV is suitable for the determination of the statistical properties of the resonance parameters.

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The Wigner Distribution of the Level Spacings

In the energy range up to 100 eV, 180 resonances were used to describe the experimental data corresponding to an average spacing of 0.55 eV for the mixed spins; 71 resonances have the spin 3\(^{-}\) and 109 resonances have spin 4\(^{-}\), with the average spacing of 1.41 eV and 0.92 eV respectively. The differential distribution of spacings is compared to the Wigner distribution for each spin state in Fig.1A and Fig.1B. For the spin 4\(^{-}\) the agreement is good, but poor for the spin 3\(^{-}\). If one assumes the spin dependence of the level spacing as \((2J+1)\exp\left[-(J+0.5)^2/2\sigma^2\right]\), the ratio of the average spacing of the two spin state should be 1.17, with \(\sigma=6.5\), showing that many more resonances should have been identified for the spin 3\(^{-}\).

The Porter-thomas Distribution of the Neutron Widths

The integral distribution of the reduced neutron widths of the 180 resonances is compared to the Porter-Thomas distribution in Fig.1C. The agreement would be good if about 20% more resonances with small values of neutron widths were added to the experimental sample. This would bring the average level spacing to a value of 0.46 eV, close to the value of 0.44 eV+0.04 eV proposed by Moore et al. Assuming a ratio of 1.17 between the two spin states, the 3\(^{-}\) level spacing should be 0.998 eV and the 4\(^{-}\) level spacing 0.853 eV. If one compares with the observed values, the missing resonances should mainly reside in the 3\(^{-}\) spin state.

The Fission Widths

The 3\(^{-}\) and 4\(^{-}\) fission channels are found in the collective levels of \(^{236}\)U, highly deformed at the fission saddle point; these levels are believed to be similar to those of the nucleus at its stable deformation. The neutron binding energy of \(^{236}\)U is 6.536 MeV and the inner fission barrier of the ground state is at 5.6 MeV above the ground state of the stable nucleus. The 3\(^{-}\) and 4\(^{-}\) levels are in the K=1\(^{-}\) to 4\(^{-}\) bands at energies between 0.7 MeV and 1.3 MeV. But it is unlikely that the energies of the levels at the saddle point are the same as those at the stable deformation. Nevertheless, at low excitation energies, the nucleus could undergo fission through few 3\(^{-}\) and 4\(^{-}\) channels at excitation energies near the neutron binding energy, but the theory cannot predict to what extent the available channels are open. Intermediate structure could also be present in the fission cross section due to the double humped nature of the fission barriers.

The integral distributions of the fission widths for the resonances in the energy interval 0 to 100 eV are given in Fig.1D and Fig.1E. The experimental distributions are compatible with a \(\chi^2\) distribution with 2 degrees of freedom. The average fission width is 225 meV for the 3\(^{-}\) resonances and 143 meV for the 4\(^{-}\) resonances, corresponding to an effective number of fission channel, \(N_{\text{eff}}=2\pi<\Gamma_f>/<D>\), of 1.42 and 1.05, respectively. Not more than one fission channel could be completely open for each spin state.

The S-wave Neutron Strength Function

The s-wave strength function is calculated according to the relation \(\sum \Gamma_j^0/(E_j-E_i)\) for each spin state in the energy range from \(E_i\) to \(E_j\), In the energy interval 0 eV to 100 eV, one obtains \((0.835\pm0.084)\times10^4\) and \((0.925\pm0.093)\times10^4\), respectively, for the 3\(^{-}\) and 4\(^{-}\) spin states. The strength function calculated by this way is not much affected by the missing levels since the method of analysis of the experimental data preserves the total area in unresolved multiplets in the total cross section. The results of the ORNL evaluation in the energy range from 0 eV to 2250 eV show that the strength function is independent of the number of resonances used to fit the experimental data, provided that experimental neutron transmissions are analyzed.
That is shown in Fig.1F which represents the variation of the sum of the analyzed reduced neutron widths versus incident neutron energy. The linear behavior of the data shows that the measured strength function does not depend on the energy.

The value of the s-wave neutron strength function obtained in the energy range 0 eV to 2250 eV (slope of the histogram of Fig.1F) is $1.073 \pm 0.027 \times 10^{-4}$. The 2.7% accuracy is due to the high number of resonances involved in this large energy range. The values for the 3\textsuperscript{\textdegree} and 4\textsuperscript{\textdegree} spin states are 1.021 and 1.107, respectively; but they do not correspond to the real values since the spins in the energy range above 100 eV were randomly assigned.

The Average Capture Width

The capture width was obtained from a SAMMY analysis of an experimental database of 14 sets of experimental data including transmission, fission and capture cross section measurements in the energy range 0 to 50 eV where the experimental resolution of the capture data was good enough to allow accurate determination of the capture area in the resonances. The individual values of the capture widths have large fluctuations from resonance to resonance, not consistent with a process involving a large number of exit channels. These strong fluctuations could be due to wrong correction of the experimental effects (background, multiple scattering, etc.) especially in the resonances with small capture cross sections at the peak. The average value for the capture width obtained from 90 individual values is equal to $(38.20 \pm 1.40)$ meV, which is consistent with a value of 36 meV from theory.

Conclusion

A complete resonance analysis of neutron transmission and cross section experimental data using the SAMMY fitting code has been carried out for $^{235}$U up to 2.25 keV. In this paper, the statistical properties of the resonance parameters have been studied. This study has provided properties and average parameters suitable for calculations in the unresolved energy region.

References

Figure 1 Statistical properties of $^{235}$U resonance parameters.