Nuclear Data for Science and Technology (1988 MITO), 783- 786,

SHIFT OF NEUTRON RESONANCE LEVELS IN PERIODIC STRUCTURE

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ABSTRACT: A large part of neutron resonance levels for the nuclei of Er-168, Hf-177 and Hf-179 are found to be located among the periodic positions of a single sequence spanned over a wide range of energy. We can use these resonances as a reference and extract the same periodic components from the other nuclei. For each of the nuclei where the extractions are successfully made, we have measured the relative shifts of the periodic positions from those of the reference nucleus. For a limited mass range of nuclei, especially, around rotational nuclei, the relative shifts show a regular pattern, which suggests the correlated behavior of the occurrence of levels among these nuclei.

(deduced relative shifts, periods, neutron resonance levels, medium and heavy nuclei)

Neutron resonance spectra are so complex that we are forced to deal with them statistically. The level spacing distributions have long been studied and compared with the statistical theory/1,2/. The existence of short range correlation (Wigner distribution) and long range correlation/3/ has been demonstrated, for example, for the Er-166 nucleus by Liou et al./4/ and for the Zn-64 nucleus by Garg et al./5/. Here the correlations come from the general properties of Gaussian orthogonal ensemble where fine structure does not appear. Search for deviations from the statistical distributions has been also made these decades. One of them is to search for particular level distances or periodicities in the level distributions/6-12/. Suchoruchkin/7/ analyzed the data for a set of combined nuclei and the authors/8-12/ for individual nuclei with medium and heavy masses. Coceva et al./9/ found the spin dependence of the 4.4 eV period in the level distribution for the Hf-177 nucleus. In Ref./10/, we looked for common periodicities among different nuclei. However, owing to the insufficient data at that time (1973), we could not make a systematic comparison among many nuclei. In the present paper, in order to find out a systematic trend in the occurrence of the periodicities, we extend our original method/8/ and make an extensive comparison among different nuclei, taking into account a recent progress in experimental data/13/.

We have used the same correlation function A20(x) as in Ref./8/ to detect dominant periodicities in the level distribution. The function A20(x) is equal to the total number of all possible pairs of levels separated at the distances which are equal to x, 2x,..., 20x within a resolution ΔE. The resolution is usually taken as $\Delta E = 0.1D - 0.2D$, where D is an average spacing between the nearest-neighboring levels. The average value and variance of A20(x) can be expressed approximately by

$$\langle A20(x)\rangle \approx 20N\frac{\Delta E}{D}\left(1 - \frac{10x}{ND}\right) \quad (1)$$

and

$$\mathrm{var}\, A20(x) \approx \langle A20(x)\rangle, \quad (2)$$

where N is the number of levels in the energy region analyzed. The validity of this approximation was checked using the simulations described in Ref./4/. Fig. 1 shows the distribution of A20(x = D) with ΔE = 0.1D for the uncorrelated Wigner distribution (U.W.) and the orthogonal ensemble (O.E.). It is seen that the Gaussian distribution well describes the fluctuation except at large deviations. We analyzed 29 nuclei of Br-79 ∿ W-186 with D = 40 - 250 eV in the energy region below 5 keV and 32 nuclei of Sb-121 ∿ Pu-242 in the energy region below 300 eV. For these energy regions, we have many nuclei for which well-resolved experimental data are given. In the energy region below 5 keV we deal mostly with even-even nuclei while in the energy region below 300 eV mostly with odd nuclei and also with several actinide nuclei. (Here we classify the resonances by target nuclei.) We obtained A20(x) with ΔE = 0.6 and 6 eV for the lower and higher energy regions respectively. Fig. 2 shows a plot of A20(x) for the Hf-179 resonances below 300 eV, where D = 4.5 eV. It is seen that large periodic peaks appear at the integral multiples of 3.06 eV with deviations of 2σ to 4σ. We also observed such peaks at the following periods ε:

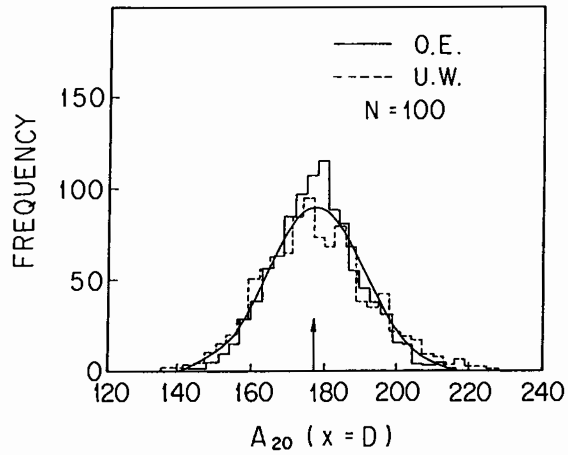

Fig. 1 Frequency distribution of A20(x=D) for the U.W. and the O.E. The arrow line indicates the average value of A20(x=D). The number of levels is 100, and the resolution is ΔE = 0.1D. The solid curve represents the Gaussian distribution whose variance is given by (2).

ε = 17.6 eV; E < 5 keV for the Er-168 resonances, where D = 68 eV,
ε = 4.37 eV; E < 300 eV for the Hf-177 resonances with J = 3, where D = 5.8 eV.

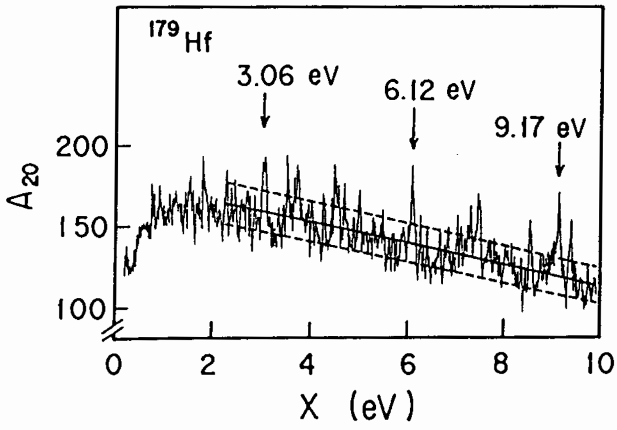

Fig. 2. Plot of A20(x) for the Hf-179 nucleus. The energy region is below 300 eV and the resolution is $\Delta E = 0.6$ eV. The solid and dashed lines indicate the average value and the standard deviation, respectively.

Here the 4.37 eV period corresponds to the 4.4 eV period in Ref./8,9/. For these three nuclei of Er-168, Hf-177 and Hf-179, we have searched for a sequence of periodic levels $n\varepsilon + \eta$ with the same period ε as determined from A20(x). Here η is a shift to the periodic levels $n\varepsilon$ starting from zero energy. Since A20(x) contains information only on the relative level distances, we have to know the shift η with another method. This is simply accomplished by counting the number of levels on the periodic points $n\varepsilon + \eta$ within a resolution ΔE, changing the value of η. We denote the number of levels on these periodic points by $L(\varepsilon,\eta,\Delta E)$, which we call a periodic component. Fig. 3 shows the plots of the periodic components vs shift for the nuclei of Er-168, Hf-177 and Hf-179. It is seen that a dominant part of levles are located on the periodic points with the same period as found in A20(x). In the figure the average value and deviations were obtained by using the following expresseions:

$$\langle L(\varepsilon,\eta,\Delta E)\rangle \approx \frac{N\Delta E}{\varepsilon} \qquad (3)$$

and

$$\mathrm{var}\ L(\varepsilon,\eta,\Delta E) \approx \frac{N(\Delta E)^2}{\varepsilon D}\left(1 - \frac{\Delta E}{D}\right). \qquad (4)$$

The approximations (3) and (4) can be used for an ensemble of uniformly distributed levels. Here the variance is estimated from the binomial distribution. In Ref./12/, the probability calculations based on this distribution were consistent with the results of the simulations. The observed deviations in Fig. 3 are larger than 4σ. Large periodic peaks in A20 usually indicate a localization of levels on the periodic points with the same period as in A20.

If two different nuclei α and β have dominant periodic components $L(\varepsilon,\eta_\alpha,\Delta E)$ and $L(\varepsilon,\eta_\beta,\Delta E)$ with the same period ε respectively, we can determine a relative shift $\Delta\eta$ which is the difference between the shifts of the two periodic components:

$$\Delta\eta = \eta_\alpha - \eta_\beta. \qquad (5)$$

Here we assume that the zero energy of the incident neutron can be a common reference point for the two different nuclei although these neutron separation energies usually differ by a large amount of several ten keV to a few MeV compared to the incident neutron energies. The relative shifts can be determined by using the function A20 in the following way. Adding a constant ξ to all the observed level energies $\{E_i\}$ of one nucleus (partner nucleus), we superpose these shifted levels on the unshifted levels of the other nucleus (reference nucleus) whose level energies are $\{E_j\}$. Then the level energies of the superposed ensemble are $\{E_i + \xi\} + \{E_j\}$. If we obtain the value of $A20(x = \varepsilon)$ as a function of ξ, the value of $A20(x = \varepsilon)$ will be largest when ξ becomes equal to a difference $\Delta\eta$ between the shifts of the periodic components for the two nuclei:

$$\Delta\eta = \eta(\mathrm{ref}) - \eta(\mathrm{part}), \qquad (6)$$

where η(ref) and η(part) denote the shifts of the periodic components of the reference and partner nuclei respectively. We call the difference as

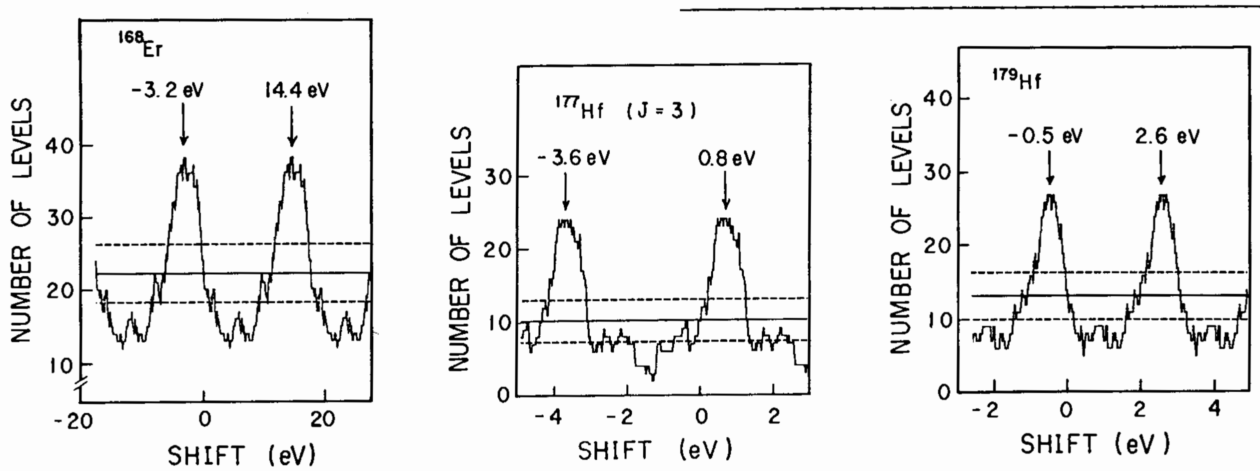

Fig. 3. Plots of periodic components vs shift for the nuclei of Er-168, Hf-177 and Hf-179. The resolution is $\Delta E = 0.2\varepsilon \sim 0.3\varepsilon$. The period is ε = 17.6, 4.37 and 3.06 eV for the nuclei of Er-168, Hf-177 and Hf-179, respectively. The solid and dashed lines indicate the average value and the standard deviation, respectively.

a relative shift. Taking each of the nuclei of Er-168, Hf-177 and Hf-179 in Fig. 3 as a reference, we measured the relative shifts of the periodic components for the nuclei we analyzed to obtain A20.

Relative shifts of the 17.6 eV components

The Er-168 nucleus was taken as a reference. Fig. 4 shows the dependence of A20(x = 17.6 eV) on the relative shifts for the nuclei of Nd-144, Nd-146, Nd-148, Sm-152 and Sm-154. It is seen that for these nuclei the maximum correlation occurs either at $\Delta\eta \approx 0$ or at $\Delta\eta \approx (1/2)\varepsilon$. There are also other nuclei for which the correlations were observed. Including these nuclei, Fig. 5 shows the relative shifts at which the maximum correlations were observed. Except for the Gd-160 nucleus, the relative shifts for the nuclei of Gd-158, Dy-162, Dy-164 and Er-166 center around the same discrete values $\Delta\eta$ = 0 and $(1/2)\varepsilon$. We calculated the probability of the occurrence of the actually observed correlation for each of the nuclei by the simulation method. Among the nuclei in Fig. 5, the Gd-160 nucleus has the weakest correlation with the reference nucleus; the probability of the occurrence is 0.03. The correlations are very strong for the other nuclei. We can observe another regular pattern. Except for two nuclei of Nd-144 and Gd-160, there is one-to-one correspondence between the isotopic components and relative shifts for the other nuclei. An increase (or decrease) of two neutrons or two protons in a nucleus makes change its relative shift by one half of the period, and after two successive operations the relative shift returns to the original value. From this standpoint, we can classify the nuclei of Nd-144 and Er-168 into the same group.

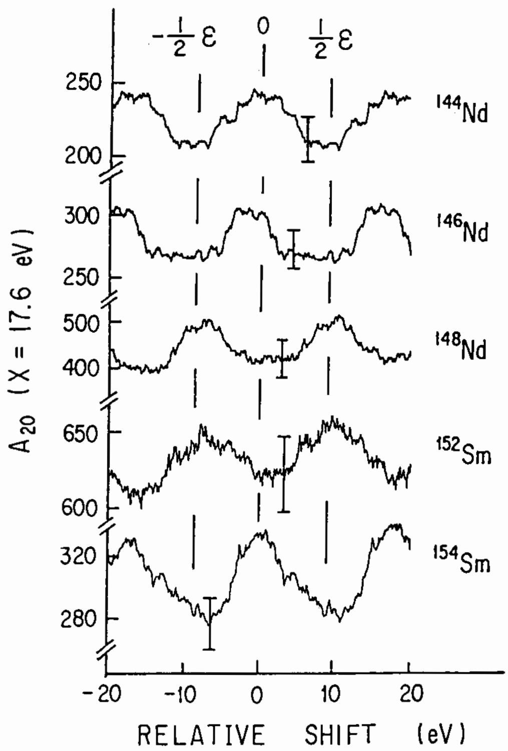

Fig. 4. Plots of A20(x = 17.6 eV) vs relative shifts. The Er-168 nucleus is taken as a reference. The energy region is below 5 keV. The resolution is ΔE = 6 eV.

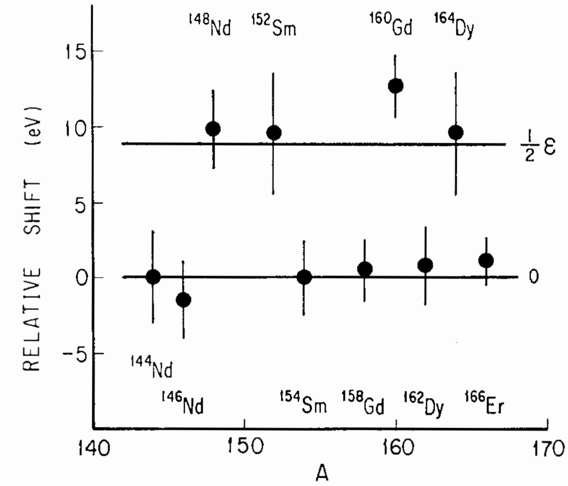

Fig. 5. Relative shifts of the 17.6 eV components. The Er-168 nucleus was taken as a reference.

Relative shifts of the 4.37 eV components

The Hf-177 nucleus was taken as a reference, and the levels with J = 3 were considered. The relative shifts of the 4.37 eV components behave in a complicated manner in many cases. However, for the nuclei of Th-232, U-234, U-236 and U-238, the relative shifts show a simple pattern. Fig. 6 shows the relative shifts for these nuclei. The strongest correlation is observed for the U-238 nucleus with $\Delta\eta \approx -(1/6)\varepsilon$. The weakest correlation is observed for the Th-232 nucleus with $\Delta\eta \approx (1/2)\varepsilon$. The probability of the occurrence is 0.08 when the random levels are superposed on the levels of the reference nucleus.

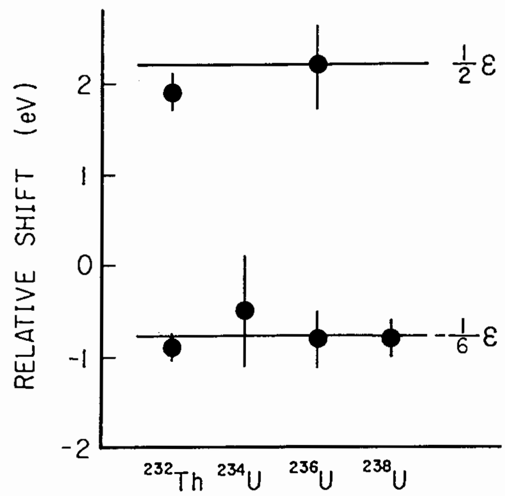

Fig. 6. Relative shifts of the 4.37 eV components. The Hf-177 nucleus was taken as a reference.

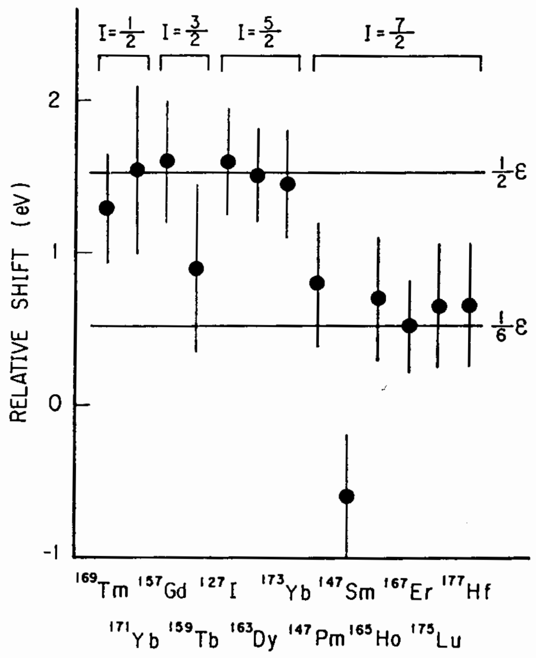

Fig. 7. Relative shifts of the 3.06 eV components. The Hf-179 nucleus was taken as a reference. Here I is the spin of the target nucleus.

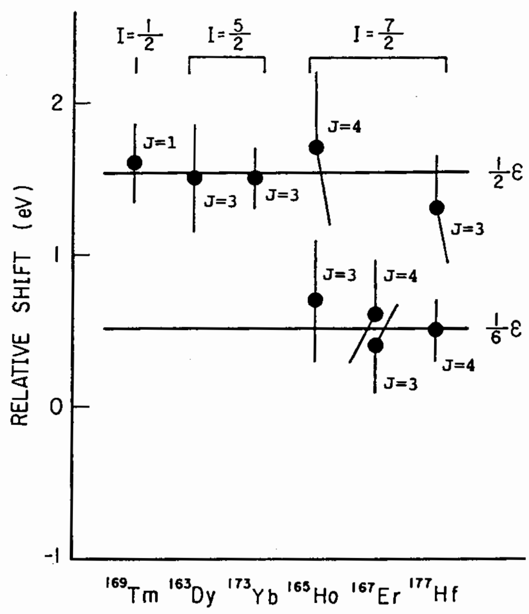

Fig. 8. Relative shifts of the 3.06 eV components. The Hf-179 nucleus was taken as a reference. Here I is the spin of the target nucleus and J the spin of the levels.

Relative shifts of the 3.06 eV components

The Hf-179 nucleus was taken as a reference. Fig. 7 shows the relative shifts for the nuclei of I-127 ∿ Hf-177. In the figure the relative shifts are grouped according to the target spins I. Except for the Sm-147 nucleus, the relative shifts center around $\Delta\eta \approx (1/2)\varepsilon$ and $(1/6)\varepsilon$. For the six nuclei for which spins $J = I \pm 1/2$ are assigned to most of the levels/13/, we obtained the relative shifts for the levels with separate spin. Fig. 8 shows these relative shifts. According to the spins J the relative shifts are separated into the two values for the Ho-165 and Hf-177 nuclei. In the case of the Ho-165 nucleus the correlation is stronger for the J = 3 levels than for the J = 4 levels, while in the case of the Hf-177 nucleus the correlation is reversed.

Our present approach to the neutron resonance spectra is simple, and the results we obtained are straightforward. But it is difficult to interprete the results in usual procedures. It is desirable that various approaches are tried to this charming realm.

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