SPIN DEPENDENCE OF THE NEUTRON FORCE FUNCTIONS OF NUCLEI

L. B. Pikel'ner

Experimental data on the difference between the force functions for the two spin states of several nuclei are analyzed, and a comparison is made with the theoretical difference due to fluctuations of the neutron width and the level spacing. More accurate experiments are required to demonstrate a spin dependence of the force function. There is a discussion of the possible determination of the force functions for the two spin states by measuring the average transmission of polarized neutrons to a polarized nuclear target.

The neutron force function $S = \overline{\Gamma}_n^0/D$ is one of the most important parameters of interest in nuclear theory and practical applications of nuclear physics. Experimental determinations of the force function are based on the two primary methods of neutron spectroscopy: study of isolated resonances and measurement of the average cross sections for neutron-nucleus interactions. These methods have yielded S values at various accuracies for most of the stable isotopes. Giant resonances have been found in the dependence of the force function on the mass number and have been explained on the basis of the optical model. As experimental data are accumulated and refined, the optical-model potential becomes more complicated.

Because of the recent progress made in the techniques and methods of studying neutron resonances, the question of a spin dependence of the neutron force functions has been raised. Identification of the resonance spins is one of the most complicated problems of neutron spectroscopy, so it is only in recent years that the spins of ten or more levels for a given isotope have been reported. The force function, defined as the ratio of the average reduced neutron width to the average level spacing, can be determined accurately only if a sufficiently large number of levels are studied, because of the broad statistical distributions of neutron widths and level spacings. For this reason, the uncertainties in the experimental values of S can usually be traced to the number of levels studied, rather than to the accuracy of the experimental data. For example, more than two hundred levels must be averaged in order to find S within 10%.

Saclay physicists have achieved important progress in studying the experimental spin dependences of the force functions [1, 2]. Through high-resolution measurements of the neutron transmission for a wide range of nuclei and a shape analysis of the data, they extracted much information about the neutron level widths and determined the spins for many of these levels. The force functions calculated separately for each spin state turned out to differ significantly in some nuclei, e.g., ^{69}Ga, ^{75}As, ^{77}Se, and ^{197}Au.

The parameters of the neutron resonances for several nuclei in the mass number range 69-87 have recently been measured at Dubna at the pulsed reactor with the microtron injector. Among the nuclei studied were some odd-A nuclei (^{77}Se, ^{69}Ga, and ^{71}Ga), for which the spins of several levels were determined through joint measurement of transmission and radiative capture [3-4]. The measurements were carried out with separated isotopes at a resolution of 3 msec/m for the transmission and 12 msec/m for the radiative capture. Comparison of our ^{77}Se data with the result reported in [10] reveals a good agreement, for both the spins and the neutron widths, at energies up to 1.5 keV, the upper limit on the data in [10]. However, the parameters which we found between 1.5 and 4 keV lead to a different conclusion re-

Joint Institute for Nuclear Research, Dubna. Translated from Problemy Fiziki Élementarnykh Chastits i Atomnogo Yadra, Vol. 2, No. 4, pp. 917-924, 1972.

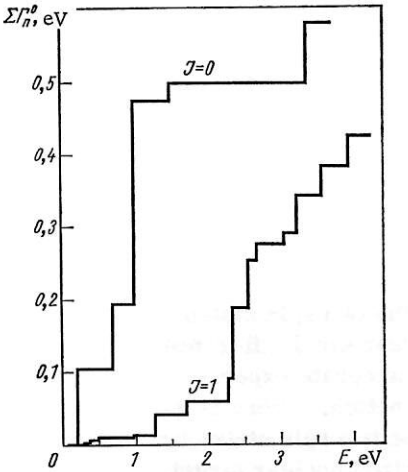

Fig. 1. Accumulating sums of the reduced neutron widths for resonances having different spins.

garding the difference between the force functions for the two spin states. The situation is illustrated in Fig. 1, which shows the accumulating sum $\Sigma \Gamma^0_{ni}$ as a function of the energy of the two spin states. The force functions determined at energies up to 4 keV are essentially the same.

No difference was found in the force functions for the two spin states for ^{69}Ga, but in this case because the spins obtained for the two levels differed from those reported in [1].

The basic criterion which has been used as evidence for a difference between the force functions of the two spin states is the small probability that this difference is random, i.e., due to statistical fluctuations. However, it is worthwhile to carry out a more detailed study of the statistical properties of the force functions and to compare the experimental data for all nuclei for which the S values are known sufficiently accurately for both spins. Such an analysis was carried out in [5], where it was shown that the use of the Porter-Thomas distribution for the reduced neutron width and Porter's calculated results [6] on the statistical distribution of energy spacings within a fixed number of levels would yield the following probability density for the experimental force function:

$$f(z, n) = C_n z^{\frac{n}{2}-1}\left(1+\frac{n}{k}z\right)^{-\frac{n+k}{2}}, \tag{1}$$

where $z = S/\langle S\rangle$ is the ratio of the experimental force function S to the actual value of $\langle S\rangle$, n is the number of resonances from which S is determined, $k = \begin{cases} 6.3\, m\sqrt{m} & \text{for } 1 \leqslant m \leqslant 9 \\ 20\, m & \text{for } m \geqslant 10 \end{cases}$, m is the experimental number of spacings between levels, and C_n is the normalization factor, which depends on n and k.

Using probability density (1), we can analyze the question of whether there is a difference between the force functions for the two spin states. Obviously, when the force functions $S(J_1)$ and $S(J_2)$ are measured for two spin states for a large number of nuclei, the statistical scatter will prevent the $S(J_1)$ and $S(J_2)$ values from being equal for a given nucleus, even if the actual values $\langle S(J_1)\rangle$ and $\langle S(J_2)\rangle$ are equal. The nature of the difference is governed by the distribution function obtained above. In this connection, the distribution of the difference between the two experimental force functions was derived in [5] under the assumption of equal actual values for these force functions:

$$\frac{dW\,(a, n^+, n^-)}{da} = \int_0^\infty f\,(a+z^-, n^+)\,f\,(z^-, n^-)\,dz^-, \tag{2}$$

where n^+ and n^- are the number of levels having spins $J_1 = I + 1/2$ and $J_2 = I - 1/2$, respectively, and $a = z^+ - z^- = (S^+ - S^-)/\langle S\rangle$ is the relative difference between the experimental values of the corresponding force functions.

However, it is inconvenient to compare the experimental data with distribution (2), since this distribution depends strongly on n^+ and n^-, which differ greatly for the various nuclei. It is more convenient to replace a by $a/\bar{\sigma}$, i.e., to analyze a in units of the standard deviation.

In this case the probability density $dW(a/\bar{\sigma}, n^+, n^-)/d(a/\bar{\sigma})$ is very nearly the same for various (n^+, n^-) pairs. From Fig. 2, which shows several such curves, we see that the curves lie quite close together, so we can say that there is a common distribution and can compare this distribution with the normalized experimental data.

To compare theory and experiment, we selected those nuclei for which the spins of at least nine resonances have been identified. For them, we calculated S^+ and S^- in a consistent manner, along with the standard deviations. From these results we constructed the histogram shown in Fig. 3, along with the theoretical curves. We see that there is no important contradiction. An evaluation on the basis of Pearson's cri-

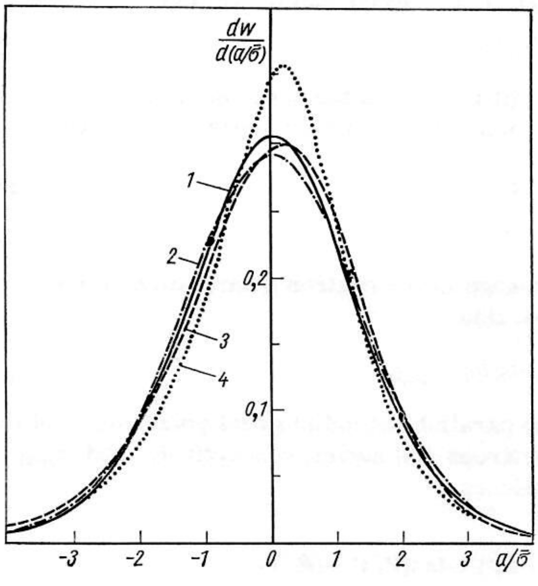

Fig. 2

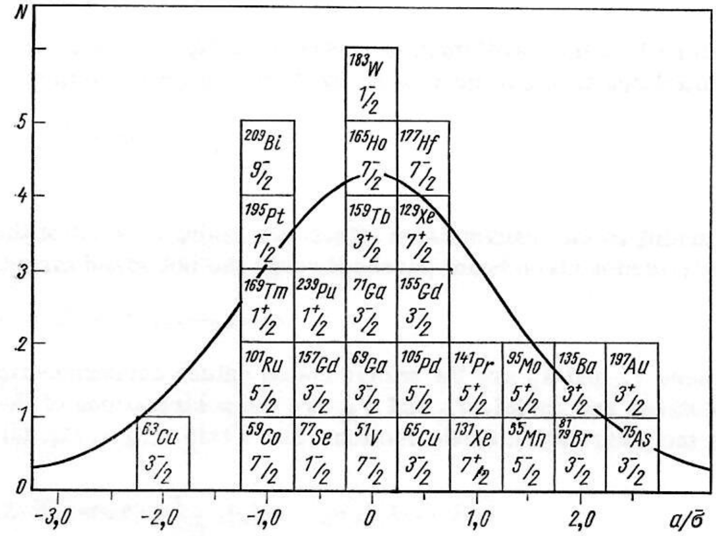

Fig. 3

Fig. 2. Distribution of $a/\bar{\sigma}$ values. 1-4) Calculated for (n^+, n^-) pairs of (12, 12), (30, 30), (20, 12), and (6, 4), respectively.

Fig. 3. Histogram of the differences between the experimental force functions for the two spin states, expressed in standard deviations. The curve is the theoretical distribution.

terion shows that the probability of finding a χ^2 value equal or greater than that found in this analysis on the basis of random deviations is 60%. Accordingly, the experimental data available for this entire set of nuclei do not contradict the hypothesis that the force functions are equal for the two spin states, and the observed cases in which there are large deviations can be completely attributed to statistical scatter. A more recent report from Saclay [7] has shown that as the energy interval is extended from 1 to 2 keV, the force functions for the two spin states of ^{197}Au become much more nearly equal.

It should be emphasized, however, that the absence of a significant effect for the entire set of nuclei in no way implies that we could not have $\langle S^+\rangle \neq \langle S^-\rangle$ for some of the nuclei. This analysis shows only that we must examine more critically the assertion that a spin dependence has been detected; a clear display of this effect requires a much better statistical accuracy for those nuclei for which a difference between S^+ and S^- has been observed. It should also be noted that the force functions might differ, not for all the nuclei, but only in certain mass-number ranges, particularly in those ranges in which the force function is a strong function of A. These features would be more difficult to detect on the basis of this analysis, particularly since there has been no theoretical prediction of the sign or magnitude of this effect.

Accordingly, the question of whether the force functions do have a spin dependence is yet to be resolved. The force functions must be determined much more accurately for the two spin states, e.g., by increasing the number of resonances to which spins have been assigned to a number at least several times greater than that of the best current measurements. Another possibility would be to extract the force function from the average cross sections through the measurement of the transmission of polarized neutrons through a polarized nuclear target. Such an experiment could be carried out with an intense beam of polarized neutrons having energies of up to tens of kiloelectron volts. The method proposed and used in the Neutron Physics Laboratory under the supervision of F. L. Shapiro could be used for this purpose: sending a neutron beam through a polarized proton target [8, 9].

Extracting the experimental force functions from the average cross sections has the advantage that an averaging is automatically carried out over a large number of resonances. Accordingly, the uncertainty in the force function is smaller than that found from fewer isolated resonances.

In the simplest case of S-wave neutrons, the average total cross section can be written

$$\langle\sigma_t\rangle = 2\pi^2 \lambda\!\!\!^{-2} \sqrt{E}\, S_0 + 4\pi (R')^2, \tag{3}$$

where λ is the wavelength of neutrons having energy E, and $4\pi (R')^2 = \sigma_p$ is the cross section for the potential scattering of neutrons. Treating the cross section for each spin component separately, we find

$$\langle\sigma_t^+\rangle = 2\pi^2 \lambda\!\!\!^{-2} \sqrt{E}\, S_0^+ + 4\pi (R_+')^2; \tag{4}$$

$$\langle\sigma_t^-\rangle = 2\pi^2 \lambda\!\!\!^{-2} \sqrt{E}\, S_0^- + 4\pi (R_-')^2. \tag{5}$$

Turning to the transmission effect, and taking account of the change in the neutron polarization as the polarized neutron beam passes through the polarized target, we find

$$\varepsilon = (T_p - T_a)/(T + T_a) = -f_n \,\mathrm{thg}\,(n f_N \sigma_{pol}), \tag{6}$$

where T_p and T_a are the transmission values corresponding to parallel and antiparallel polarization of the neutrons and nuclei, f_n and f_N are the polarizations of the neutrons and nuclei, respectively, and σ_{pol} is the polarization cross section. For a thin target, Eq. (6) reduces to

$$\varepsilon = -n f_n f_N \sigma_{pol} = n f_n f_N \frac{I}{2I+1} \{2\pi^2 \lambda\!\!\!^{-2} \sqrt{E}\, (S_0^+ - S_0^-) + 4\pi [(R_+')^2 - (R_-')^2]\}. \tag{7}$$

We see from this expression that by measuring the transmission effect ε we can find the difference $S_0^+ - S_0^-$ if the difference $(R_+')^2 - (R_-')^2$ has been measured separately, e.g., on the basis of the interval between the resonances or the resonance shape due to the interference of the resonance and potential scattering for the difference spin states.

We can estimate the expected transmission effect by substituting the actual values into Eq. (7): $\varepsilon \approx 0{,}05 \left[\frac{S_0^+ - S_0^-}{\langle S_0\rangle} + \frac{(R_+')^2 - (R_-')^2}{\langle (R')^2\rangle}\right]$. We see that in order to find a difference on the order of 10% between the force functions we must measure the transmission effect within 0.5%. This is not a simple task, but it is an entirely possible one, and could be carried out on the IBR reactor with the injector and polarized target.

LITERATURE CITED

1. J. Julien et al., Phys. Lett., 10, 86 (1964).
2. J. Julien, International Conference on the Study of Nuclear Structure with Neutrons, Antwerp (1965).
3. H. Malecki, et al., Yad. Fiz., 9, 1119 (1969).
4. H. Malecki et al., Preprint R3-4152, JINR, Dubna (1968).
5. H. Malecki et al., Yad. Fiz., 11, 111 (1970).
6. C. E. Porter, J. Math. and Phys., 4, 1039 (1963).
7. R. N. Alves et al., Nucl. Phys., A131, 450 (1969).
8. Yu. V. Taran and F. L. Shapiro, Zh. Éksp. Teor. Fiz., 44, 2185 (1963).
9. V. P. Alfimenkov et al., Yad. Fiz., 3, 55 (1966).
10. J. Julien et al., Phys. Lett., 3, 67 (1962).