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NEUTRON RESONANCE PARAMETERS OF ^{177}Hf

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1. Introduction

In order to investigate the formation and decay processes of excited nuclei in neutron induced reactions, a setup based on a 16-section NaJ(Tl) scintillation gamma-detector was created at the pulsed neutron booster IBR-30 of the Joint Institute for Nuclear Research in Dubna[1]. This detector is a version of the Romashka-type detectors used by Muradyan[2] and it provides the possibility of measuring the gamma-quanta and neutron multiplicity, neutron cross sections and their ratios with a high degree of precision. The multiplicity spectrometry applied in coincidence with the time-of-flight technique supplies broad information about the processes in the neutron resonance energy region and especially the characteristics of the compound nucleus resonance levels.

During the last few years a certain number of nuclei were investigated in Dubna by the method of multiplicity spectrometry in order to obtain their resonance parameters [3,4,5,6]. These experiments were based on the technique of simultaneous measurement in identical conditions of radiative capture and neutron scattering events with the Romashka detector. An other purpose of our measurements was the search for spin dependence of the neutron strength function in the energy region of the resolved resonances.

The spin of the resonances was determined by the γ-cascade multiplicity method[7]. The essence of this method is based on the fact that, except for transitions between low-lying states, dipole radiation is predominant in the capture gamma spectrum[8]. As a consequence, the spin change involved at each step of the γ-cascade is mostly zero or one. It seems then reasonable to assume that the average number of steps per cascade should have a strong dependence on the difference between the spins of the initial and final states. Consequently, we may say that the average number of emitted gamma-rays per neutron capture, the probability distribution of the multiplicity and average gamma-energy spectrum should be spin-dependent. In view of this, it is worthwhile using a multidetector system in order to register simultaneously most of the emitted γ-quanta, i.e. the multiplicity of the gamma-quanta cascade.

The aim of this work was to determine the spin of the two series of states, excited by low-energy s-wave neutron capture in an odd-neutron nucleus ^{177}Hf($I = 7/2$), and to check whether the J=4 level density is changing above the 300 eV energy range. The other purpose was to evaluate the neutron strength function and to search for the spin dependence of such a value.

The ^{177}Hf nucleus is one of the examples, where an almost complete spin determination of a large set of neutron resonances has been achieved[9]. In this paper is shown a significant loss of levels above 180 eV for the J=3 series and above 100 eV for J=4. The authors repeated the analysis of Ideno and Ohkudo[10] and found that the J=3 series shows a marked preference for positions separated by a characteristic spacing of 4.4 eV, while the J=4 series is consistent with an uncorrelated distribution. The attribution of the correlation found by Ideno and Ohkudo, and attributed by Coceva to the J=3 series, suggests that this effect is of physical relevance, and it may be considered as a symptom of a not yet fully statistical behaviour of the ^{178}Hf levels.

In view of this, it is desirable to study the spin of the ^{177}Hf resonances above 300 eV.

2. Method of analysis

To obtain the value sensitive to the spin of the levels let us consider the plot in fig.1. This figure shows the frequency distribution of the γ-cascade multiplicity obtained in our experiment for the two spin values of s-wave resonances in target ^{177}Hf. It is evident from the plot, that the J=3 effect is stronger in the region of m1 and m2-fold coincidence, than the J=4 effect predominate in the region from m3 to m6-fold coincidence. We define now the ratio $R(J,E_0^i)$ between the two sums, given by the relation:

$$R(J,E_0^i)=\frac{\sum\limits_{mk=1}^{2}A_{mk}(E_0^i)}{\sum\limits_{mk=3}^{6}A_{mk}(E_0^i)} \tag{1}$$

where $A_{mk}(E_0^i)$ is the peak area of the resonance with energy E_0^i in the time-of-flight spectrum of mk-fold coincidence. As is obvious from the fig.1. , the ratio R is spin sensitive and may be used to deduce the spin of the resonances. This ratio may be defined for separate time-of-flight channels:

$$R(J,N(E_n))=\frac{\sum\limits_{mk=1}^{2}N_{mk}(E_n)}{\sum\limits_{mk=3}^{6}N_{mk}(E_n)} \tag{2}$$

where $N_{mk}(E_n)$ is the count per time channel, corresponding to the neutron energy E_n in the time-of-flight spectrum of mk-fold coincidence.

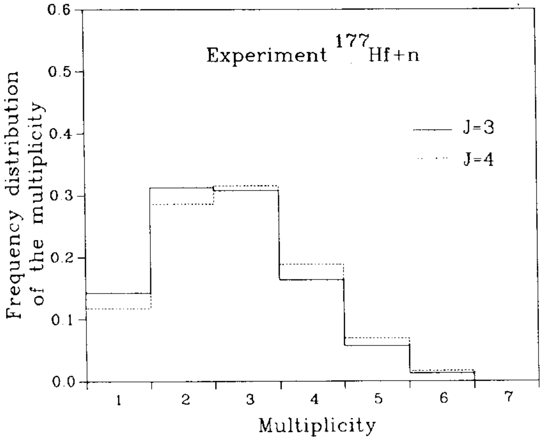

Fig1. Frequency distribution of the γ-ray multiplicity.

3. Experiment

The experiment was carried out at the IBR-30 booster of JINR, Dubna, used to produce a pulsed neutron source. The booster was operated at an average beam power of 10 kW, with neutron pulses 4 μs wide, at a repetition frequency of 100 Hz. The neutron energy was determined by the time-of-flight technique on a 502 m long flight path, so that the energy resolution was 8 ns/m.

The detector consisted of 16 independent NaJ(Tl) crystal sections with a total volume of 36 litres and geometric efficiency of 80%. The capture measurement was performed with a sample of $3.34.10^{-4}$ nuclei/barn of HfO_2 enriched up to a 85.4% abundance. The sample was borrowed from the Institute for Nuclear Research and Nuclear Energy in Sofia - Bulgaria. The complete measuring time for determining the spin of ^{177}Hf resonances was 150 hours.

4. Results

We assigned resonance J value in ^{177}Hf between 20 and 310 eV, and our result is in agreement with the data of ref.[11], except the resonances 66.69 eV, 122.7 eV, 136.2 eV and 299.7 eV.

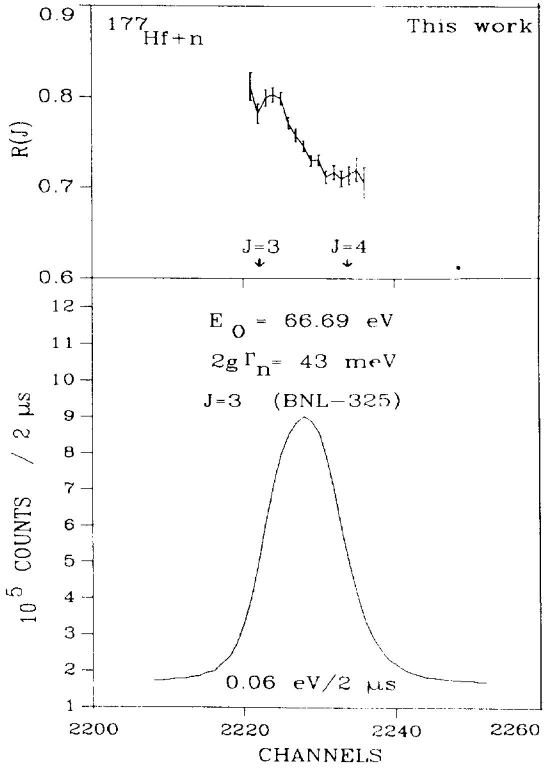

Fig. 2. A spin determination of two strongly overlapping levels.

A particular problem is posed by the resonance at 66.69 eV. Although it looks like a single resonance even in a high resolution measurements, its behaviour in spin analysis belong to neither spin group. This resonance, assigned as J=3 in ref.[11], has been reanalysed by Coceva, using a shape fitting code and additional information from capture gamma-ray spectra, and, also, by Stefanon and Corvi[12]. According to these authors, the resonance is a doublet of different spins and nearly equal contribution to the capture area. Our investigation confirmed this fact. Fig.2 shows the behaviour of the ratio R versus the channel number of the time-of-flight spectrum, i.e. versus the neutron energy. That this peak results from a very close overlapping of two resonances with different spins is evident.

Moreover, we assigned the spin of the resonances between 300 and 700 eV. In this energy region 76 resonances were observed (all available in BNL-325, and the spin was determined for 74 of them (see tab.1).

Table 1. Energies and spins of ^{177}Hf resonances.

E_0[eV]	J	E_0[eV]	J	E_0[eV]	J	E_0[eV]	J
302.4	(3)	398.8	(3)	472.2	4	591.1	4
307.0	3	406.2	4	475.0	4	596.9	(3)
311.0	3	408.8	4	478.7	3	599.1	(4)
313.6	3	412.9	4	481.6	(4)	604.7	3
319.9	4	414.9	4	488.6	3	610.4	4
323.6	4	418.8	4	498.5	4	612.5	4
327.5	4	426.1	3	507.2	4	618.9	4
330.4	4	429.2	4	512.2	4	625.5	-
333.4	4	431.7	3	520.7	3	628.7	4
341.8	4	433.6	3	523.0	4	633.2	-
348.7	3	434.9	(4)	525.5	3	640.6	4
354.7	3	435.9	4	533.2	4	646.4	4
357.1	4	443.4	4	539.1	4	653.9	4
362.3	(4)	446.6	3	541.3	4	657.8	4
367.5	4	449.4	4	548.6	4	669.2	3
370.7	4	453.8	3	557.2	3	676.5	3
375.6	4	457.4	3	573.7	3	684.7	3
389.8	3	466.6	3	577.4	3	693.1	4
393.6	4	470.8	3	581.9	3	696.6	4

The cumulative graphs of fig.3 show the same tendency as below 300 eV, i.e. an apparent loss of levels. For instance, at 700 eV the J=3 staircase is 45 levels too low with respect to the straight line, and the J=4 staircase is too low by 80 levels. The fig.3 substantiate the fact of a progressive density fall of the both series in the energy interval between 100 and 700 eV. The ratio of the observed level densities in the range from 0 to 700 eV, obtained by means of our spin identification (there are 6 spin unassigned resonances) is $(2J+1)^{exp.} = 1.26$, while the theoretically prediction is $(2J+1)^{th.} = 1.29$.

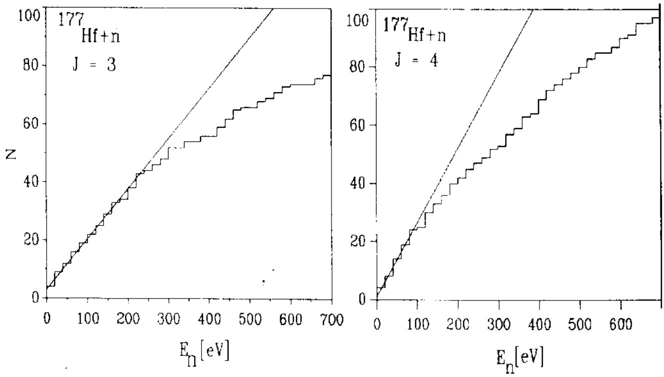

Fig. 3. Cumulative graph of ^{178}Hf levels assigned to J=3 and J=4.

A direct evaluation of the neutron strength function from Γ_n data of ref.[11] and our spin assignment (below 20 eV spins of ref.[11] was made for the complete energy range 0-700 eV as well as for the partial energy ranges of 100 eV. The results are given in table 2. The errors in the table taken into account statistical errors and the fluctuations in the evaluation of Γ_n. In the present analysis the capture areas of the unresolved doublet at 66.69 eV and of the other resonances with unassigned spin have been attributed to equal parts to two groups with J=3 and J=4. The strength functions for the two spin series, as calculated from the complete energy range 0-700 eV, were found to be coincident within the errors. However, the strength function for J=4 shows a significant energy dependence. For instance, in the intervals 100-200 eV and

Table 2. S-wave neutron strength functions of ^{177}Hf for different energy intervals.

Energy interval [eV]	$S_0(J^\pi = 3^-)$	$S_0(J^\pi = 4^-)$
0 ÷ 100	$.96^{+0.92}_{-0.49}$	$3.83^{+1.50}_{-0.92}$
00 ÷ 200	$2.56^{+1.28}_{-0.60}$	$.19^{+0.60}_{-0.32}$
200 ÷ 300	$3.56^{+1.94}_{-1.00}$	$.58^{+1.02}_{-0.43}$
300 ÷ 400	$.74^{+1.88}_{-0.61}$	$4.24^{+2.58}_{-1.34}$
400 ÷ 500	$4.04^{+3.26}_{-1.36}$	$3.16^{+1.95}_{-0.90}$
500 ÷ 600	$2.27^{+2.67}_{-0.81}$	$.54^{+1.40}_{-0.52}$
600 ÷ 700	$.95^{+3.72}_{-0.86}$	$3.36^{+2.59}_{-1.08}$
0 ÷ 300	$2.69^{+0.65}_{-0.49}$	$2.20^{+0.53}_{-0.40}$
300 ÷ 700	$2.50^{+0.98}_{-0.60}$	$3.08^{+0.82}_{-0.56}$
0 ÷ 700	$2.58^{+0.47}_{-0.34}$	$2.70^{+0.35}_{-0.29}$

300-400 eV, there is a change by more than a factor of three. The high value of the strength function for J=4 in the intervals 0-100 eV and 300-500 eV is caused by very strong resonances in these intervals.

In the plot (fig.4.) of the cumulative sum of the reduced neutron widths, one can see an apparent change of the slop of the staircase for J=4 and abrupt ascents separated by a constant intervals of 300 eV. As it is shown by Rohr and Weigman[13] in the energy interval below 300 eV, such ascents could represent narrow "intermediate" structures with a spreading width.

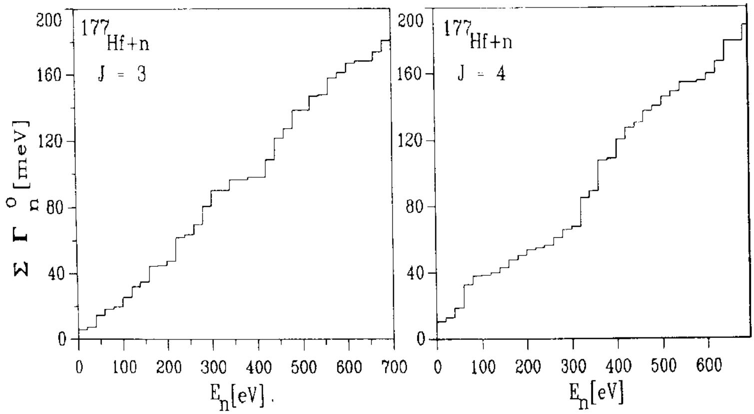

Fig. 4. Cumulative sum of reduced neutron widths as a function of energy.

5.Conclusion

The spin has been determined of the 180 resonances of ^{177}Hf up to 700 eV, excluding 6 weak levels. New experimental data is obtained on the spin of the resonances between 300 and 700 eV. The results of this work once more shown the possibility of the γ-ray multiplicity method for determining the spin of the resonances, even in the case of strongly overlapping levels, such as those at 66.69 eV. A direct evaluation of the neutron strength function from Γ_n data of BNL-325 and our spin identification is made for the complete energy range 0-700 eV as well as for partial energy ranges of 100 eV. Our results confirm the nonstatistical behaviour of the ^{178}Hf levels. We have observed a progressive density fall and a statistically significant energy dependence of the strength function for J=4 in the energy interval between 0 and 700 eV. It is therefore necessary to carry out an experiment to investigate the statistical behaviour of the strength in the energy region of the unresolved resonances.

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Параметры нейтронных резонансов ^{177}Hf

Множественность гамма-лучей от реакции ^{177}Hf + n измерялась в нейтронно-спектроскопическом эксперименте по методу времени пролета с помощью 16-секционного NaJ(Tl) сцинтилляционного детектора «Ромашка». Получены новые экспериментальные данные для спина нейтронных резонансов в области от 300 до 700 эВ с помощью метода спектрометрии множественности гамма-лучей. Показана возможность этого метода для идентификации перекрывающихся резонансов с различающимися спинами. Определены силовые функции в интервале от 0 до 700 эВ — $S_0 = (2{,}70^{+0{,}36}_{-0{,}29})\cdot 10^{-4}$ для $J = 4$ и $S_0 = (2{,}58^{+0{,}47}_{-0{,}34})\cdot 10^{-4}$ для $J = 3$, которые равны в пределах ошибок.

Работа выполнена в Лаборатории нейтронной физики им. И.М.Франка ОИЯИ.

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Neutron Resonance Parameters of ^{177}Hf

The capture gamma-ray multiplicity in the reaction ^{177}Hf + n was measured by a 16-section NaJ(Tl) scintillation detector in a time-of-flight neutron spectroscopy experiment. Between 300 and 700 eV new experimental data were obtained on the spins of the resonances, making use of the gamma-cascade multiplicity method. The possibility of this method for identification of strongly overlapped resonances with different spin is shown. In the energy interval from 0 to 700 eV, the strength functions obtained as $S_0 = (2.70^{+0.36}_{-0.29})\cdot 10^{-4}$ for $J = 4$ and $S_0 = (2.58^{+0.47}_{-0.34})\cdot 10^{-4}$ for $J = 3$, were found to be coincident within the errors.

The investigation has been performed at the Frank Laboratory of Neutron Physics, JINR

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