

FORSCHUNGSZENTRUM KARLSRUHE

Technik und Umwelt

Wissenschaftliche Berichte

FZKA 5968

NEUTRON CAPTURE RESONANCES IN

^{142}Nd AND ^{144}Nd

K. WISSHAK, F. VOSS, and F. KÄPPELER

Institut für Kernphysik

Forschungszentrum Karlsruhe GmbH, Karlsruhe
1997

Abstract

The neutron capture cross sections of ^{142}Nd and ^{144}Nd which were determined recently with the Karlsruhe $4\pi\text{BaF}_2$ detector have been reanalyzed at low energies. This work includes also a detailed discussion of the corrections for sample impurities. The parameters of 52 resonances in ^{142}Nd and of 78 resonances in ^{144}Nd were extracted by means of a shape analysis program, yielding a more reliable determination of the averaged cross sections below 20 keV. This study confirms the previously reported stellar cross sections, so that the s-process study based on these data remains unchanged.

Zusammenfassung

NEUTRONENEINFANGRESONANZEN IN ^{142}Nd UND ^{144}Nd

Die kürzlich mit dem Karlsruher $4\pi\text{BaF}_2$ Detektor gemessenen Neutroneneinfangquerschnitte von ^{142}Nd und ^{144}Nd wurden bei niedrigen Energien neu ausgewertet. Außerdem wurden die Korrekturen für Probenverunreinigungen im Detail diskutiert. Mit einem Analyseprogramm wurden die Parameter von 52 Resonanzen in ^{142}Nd und von 78 Resonanzen in ^{144}Nd ermittelt, die eine genauere Bestimmung der Querschnitte unterhalb von 20 keV ermöglichen. Die neuen Ergebnisse bestätigen die früher veröffentlichten stellaren Querschnitte. Daher bleiben die Untersuchungen zum s-Prozess, die auf diesen Daten basieren, unverändert gültig.

1 Introduction

The experimental situation of neutron capture in neodymium isotopes is quite peculiar. With six reported measurements per isotope, neodymium is one of the most frequently investigated elements. However, for each isotope the individual results differ by factors of two to three [1]. Hence, a reliable set of cross sections is urgently required for s- and r-process studies [2].

In an attempt to improve the experimental data, the neutron capture cross sections of the six neodymium isotopes ^{142}Nd , ^{143}Nd , ^{144}Nd , ^{145}Nd , ^{146}Nd , and ^{148}Nd were measured using the Karlsruhe $4\pi\text{BaF}_2$ detector for registration of capture events [2]. Compared to previous results, a five times better accuracy could be achieved for the stellar cross sections at $kT=30$ keV, and, for the first time, reliable values were also obtained at lower temperatures for a complete set of isotopes. With these data the s-process abundances of the neodymium isotopes could be described quantitatively.

In this study, the differential capture cross sections of ^{142}Nd and ^{144}Nd were measured with sufficient resolution that single resonances could be resolved up to about 20 keV neutron energy. Despite of this feature, the stellar cross sections were first determined by averaging the observed capture yield [2]. This simplification may be justified to good approximation according to a similar study on ^{134}Ba [3] and on three tin isotopes [4]. On the other hand, the cross section at these low energies could be affected by the treatment of the a significant background due to capture of scattered neutrons. The isotopes ^{144}Nd and ^{145}Nd are particularly sensitive in this respect due to their extremely large s-wave strength function, that is exceeded only by a few isotopes in the mass range around $A = 50$ [5]. Therefore, the response of the experimental setup to scattered neutrons is rather critical for a reliable determination of the comparably small (n,γ) cross section of ^{144}Nd .

The present work deals with the quantitative analysis of impurities in the Nd samples used in the measurement of Ref. [2], which were initially specified without uncertainties. The second aim is the reanalysis of the cross sections reported in Ref. [2] by means of a shape analysis program for determining the resonance parameters. From these parameters new and more reliable data for the low energy part of the stellar cross sections were derived, an improvement, that is especially important, since stellar model calculations indicate that most of the s process proceeds via the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction at thermal energies of 10 keV or less [6, 7].

2 Activation analysis of the sample material

The contaminations of isotopically enriched samples by other elements are in general derived from spectroscopic analyses. In most cases, the corresponding corrections were marginal and had no impact on the actual results. Though the chemical relationship among the rare earth elements may favor such contaminations, these effects were still very small in the previous experiments on samarium and gadolinium isotopes where the investigated cross sections were compatible with those of the impurities. However, this is different for the Nd isotopes. For example, the cross sections of ^{142}Nd and ^{151}Eu differ by a factor of 130, leading to significant corrections even for tiny admixtures.

The specifications of the ^{142}Nd sample included Pb (0.11%) and the rare earth elements Ce (0.44%), Pr (0.10%), Sm (0.16%), and Eu (0.04%). Similar impurities were quoted for the ^{143}Nd sample, while the other four samples showed contaminations which were much smaller or below the detection limit. The required corrections were estimated via the Maxwellian averaged cross sections at 30 keV and by using an effective binding energy of the impurity isotopes to account for the limited overlap with the γ -ray spectrum of true capture events in ^{142}Nd (binding energy 6.1 MeV). While the Pb, Pr, and Ce contaminations are unimportant due to their small cross sections, the specified Sm and Eu admixtures would have implied critical corrections. The effective cross section of elemental europium being about 100 times larger than that of ^{142}Nd would have required a reduction of the measured cross section by 4%. Correspondingly, the samarium correction had caused an additional reduction by 1.6%.

Since the reliability of the specified chemical data was unclear, a new analysis was performed via the neutron activation technique. About 10 mg of the most critical samples enriched in ^{142}Nd , ^{143}Nd , and ^{144}Nd were irradiated for four hours in a thermal neutron flux of $\sim 10^{13} \text{ s}^{-1} \cdot \text{cm}^{-2}$. The induced activities were calibrated by three samples of natural europium (33 to 136 μg), which were irradiated simultaneously. After a cooling period of 7 days, γ -ray spectra taken with a germanium detector showed all rare earth impurities.

In order to improve the signal/background ratio for the weak lines from the decay of the long-lived ^{152}Eu , the measurement was repeated after a cooling period of 42 days. Then, the lines at $E_\gamma = 344.3$, 778.9 and 1408.0 keV from the β^- and electron capture decay of ^{152}Eu could be analyzed for all three samples and were used to determine the impurities listed in Table 1. The specific activities of the three europium standards agreed within $\pm 10\%$. This uncertainty is mainly due to the mass determination and probably to neutron self-absorption effects, while most other parameters cancel out in this relative measurement, e.g. neutron flux, thermal capture cross section, decay intensities, and detector efficiency.

Due to the shorter half-lives of the corresponding reaction products, the other rare earth impurities could be evaluated from the first set of data. Since standard samples were used only for the Eu component, the before mentioned parameters had to be considered explicitly, leading to somewhat larger uncertainties in the results for La, Ce, Pr, and Sm listed in Table 1. The general element pattern shows a bell shaped distribution around neodymium.

In order to get an idea of the uncertainties involved, the known abundances of ^{146}Nd , ^{148}Nd , and ^{150}Nd were evaluated as well. The results given in Table 1 are systematically lower by a factor of 0.67 compared to the values derived from the isotopic composition, but are otherwise in good agreement for all isotopes. This indicates that cross sections, decay intensities, and the detector efficiency were treated correctly, but that the effective neutron flux was overestimated. The two main cerium isotopes, ^{140}Ce and ^{142}Ce , could be separated in the analysis as well, with ^{142}Ce being enhanced by a factor of 2.5 compared to the natural abundance ratio.

In summary, it was shown that the detected impurities were much smaller than quoted in the original specifications. Accordingly, the corresponding corrections are very small, and the systematic uncertainties assigned in Ref. [2] represent conservative estimates.

Table 1: Impurities in the enriched ^{142}Nd , ^{143}Nd , and ^{144}Nd samples

	Sample			Decay Parameters ¹	
	^{142}Nd	^{143}Nd	^{144}Nd	γ -Energy (keV)	Half-life
Sample Mass (mg)	12.1	11.6	5.8		
Mass of detected impurities					
La (μg)	0.05	0.06	0.03	1596.2	40.3 h
Ce (μg)	2.0	1.4	0.6	145.4(^{141}Ce), 293.3(^{143}Ce)	32.5 d, 33.0 h
Pr (μg)	15.	3.	$\sim 3.$	1575.9	19.1 h
Sm (μg)	0.07	0.24	0.11	103.2(^{153}Sm)	46.3 h
Eu (μg)	0.005	0.011	0.006	344.3, 778.9, 1408.0(^{152}Eu)	13.5 yr
Mass of Nd isotopes derived from activation analysis					
^{146}Nd (μg)	22.7	98.3	72.1	531.0, 91.1	11.0 d
^{148}Nd (μg)	4.6	8.6	4.2	286.0	53.1 h
^{150}Nd (μg)	3.6	4.7	1.7	340.0	28.4 h
Mass of Nd isotopes calculated from isotopic composition					
^{146}Nd (μg)	32.7	149.6	101.5		
^{148}Nd (μg)	7.3	12.8	6.4		
^{150}Nd (μg)	4.8	5.8	3.5		

¹ γ -intensities per decay were adopted from Ref. [8]

3 Experiment and data evaluation

Experiment and data analysis have been described in detail in Ref. [2]. Continuous neutron spectra were produced via the $^7\text{Li}(p,n)^7\text{Be}$ reaction using the pulsed proton beam of the Karlsruhe 3.75 MV Van de Graaff accelerator. Capture events were registered with the Karlsruhe $4\pi\text{BaF}_2$ detector [9] with a time resolution of about 1 ns. The samples, enriched to 95.5% in ^{142}Nd and 82.1% in ^{144}Nd , were located at a neutron flight path of 78 cm. The sample mass was 7.0 and 7.4 g, and the thickness 6.3 and $5.5 \cdot 10^{-3}$ A/b, respectively. Four runs were performed with different maximum neutron energies and acquisition modes [2]. All time-of-flight (TOF) spectra could be analysed down to a minimum neutron energy of 3 keV, but the run with 200 keV maximum neutron energy was omitted in the present analysis due to its smaller signal to background ratio at low energies.

After summation of the capture yields from the three other runs, the resulting TOF spectra were analysed with the FANAC code [10] in the same way as described for ^{134}Ba [3]. The global input parameters like strength functions or nuclear radii were the same as in the calculations of the multiple scattering and self-shielding corrections described in Ref. [2]. Known neutron widths of s- and p-wave resonances as well as resonance spins were adopted from the JENDL-3 evaluation [11].

The TOF measurement of the neutron energy is determined by the pulse width of the proton beam (0.7 ns), the time resolution of the $4\pi\text{BaF}_2$ detector (0.5 ns), and by the sample thickness (4.6 mm) resulting in an average resolution in neutron energy of ± 55

eV at 10 keV, ± 35 eV at 7 keV and ± 23 eV at 5 keV. Thus, the shape of the very broad s-wave resonances is to a large extent determined by the experimental resolution which means that it was not possible to derive the individual resonance parameters g_n or γ_n directly from the present experiment. Instead, the resonance area $A_\gamma = g_n \gamma_n / (g_n + \gamma_n)$ was determined in the fits.

If no information on g_n is available the average neutron width can be calculated via the relation [12]

$$g_n \langle \gamma_n \rangle_{lJ} = \nu_{lJ} g_J D_J S_l \sqrt{E} v_l(E) \quad (1)$$

where the quantities g , D , S , ν , and v_l denote the statistical weight factor, the mean level spacing, the strength function, the number of possible channel spins, and the penetrability factor for the respective orbital angular momenta l . For p-wave resonances, this expression reduces to

$$g_n \langle \gamma_n \rangle_1 = D_s S_1 \sqrt{E} \frac{(kR)^2}{1 + (kR)^2}. \quad (2)$$

The reliability of the resonance areas A_γ depends on the available experimental information on neutron widths and spins. For the two neodymium isotopes under consideration the situation is much more favorable compared to the previously investigated tin and barium isotopes [3, 4]. As discussed in these references, the systematic uncertainties of the resonance analysis depend on the quality of the available s-wave neutron widths. These data are most critical for ^{144}Nd due to its large s-wave strength. For both investigated isotopes the neutron widths of all s-wave resonances are provided by the JENDL-3 evaluation [11]. For p-wave resonances all g and g_n values are known for ^{142}Nd while for ^{144}Nd this information exists up to 11.7 keV. At higher energies, the g_n were calculated according to Eq.(2) and the g values were arbitrarily set to unity. The systematic uncertainties due to lacking neutron widths and g values can be neglected in the present study.

In a first step the energies of well isolated resonances were determined. The comparison with a recent high resolution experiment by Guber et al. [13] showed that the energy differences are linearly increasing with resonance energy. Hence, this relation was used to calculate the resonance energies for all unresolved multiplets consistent with the energy scale of Ref. [13]. These energies were then adopted as fixed parameters in the fits. In the second step, all resonance areas were determined. These results are given in Tables 2 and 3. For a few exceptions (2 cases in ^{142}Nd and 6 in ^{144}Nd , mostly for p-wave resonances close to an s-wave resonance), the p-wave areas of Ref. [13] were directly used as fixed input parameters to obtain a more reliable fit of the nearby s-wave resonance. The quoted statistical uncertainties are those provided by the FANAC code. The experimental capture yields and the FANAC fit are compared in Figs. 1 and 2. The gaps in the data correspond to energy intervals without significant resonances.

If the resonance energies are compared with the values given by Mughabghab *et al.* [5], JENDL-3 [11], and Guber et al. [13], one finds that around 4 keV all data sets agree on average to better than 6 eV for ^{142}Nd and to better than 10 eV for ^{144}Nd . With increasing energy, there are linearly increasing differences. At an energy of 15 keV, these

differences have reached values (in the order of the above citations) of 30, 100, 50 eV for ^{142}Nd and of 0, 0, 60 eV for ^{144}Nd , respectively. These deviations are compatible with an uncertainty of ~ 1 mm in the flight path of the present experiment which translates into a 40 eV uncertainty in the resonance energy at 15 keV. The large discrepancy with respect to the JENDL-3 data for ^{142}Nd is somewhat surprising since the data sets of Refs. [5, 11] are based on the same experimental results [14].

As far as the resonance areas are concerned there is good agreement for the p-wave resonances of ^{142}Nd . The sum of all p-wave areas obtained in the various experiments agrees within 4%, and the scatter of individual resonance areas is in most cases less than $\pm 20\%$, compatible with the statistical uncertainties and with the fact that the limited energy resolution of the present experiment hampers the separation of multiplets.

For the s-wave resonances in ^{142}Nd the situation is different, however. Though the sum of all s-wave areas exceeds the value of the other data sets by only $\sim 7\%$, the individual areas scatter by more than a factor of two. There seem to be several systematic effects involved which cancel out in the sum. The most prominent examples are the resonances at 3.382, 9.019, 13.66, and 16.26 keV. The resonance areas of the first two resonances, which exhibit very small neutron widths, are systematically larger by 50 to 100% compared to the values of Refs.[5, 11, 13], whereas the areas of the two other resonances, which have very large neutron widths, are lower by nearly a factor of two. These discrepancies for s-wave resonances might arise in experiments using long flight paths and the pulse height weighting technique due to problems with the neutron sensitivity and/or with the weighting function in case of resonances with very hard capture γ -ray spectra. Though these problems have been widely discussed in the past they seem to persist, in particular in case of neutron magic nuclei such as ^{142}Nd , which are likely showing hard capture γ -ray spectra.

The comparably strong resonance at 7.627 keV is not listed in the older data, but has also been found by Guber *et al.* [13]. Adopting their s-wave assignment and assuming a neutron width of 600 meV according to the similar shape compared to neighboring resonances yields a resonance area of 82.1 ± 4.9 meV. However, even an extreme neutron width of 8000 meV, estimated via Eq. (1), has little impact on the resonance area, which then reduces to 76.2 meV.

In case of ^{144}Nd the situation is more complex. The sum of all present p-wave and s-wave areas are 60% and 70% higher than the respective values in the compilations of Mughabghab [5] and JENDL-3 [11] which are both based on the experiment by Musgrove *et al.* [14], indicating a severe normalization uncertainty. Compared to the work of Guber *et al.* [13] our results are systematically higher by 10% for the p-wave, but 33% for the s-wave resonances in the range below 15 keV. Here again differences up to a factor of two occur for individual resonances but – in contrast to ^{142}Nd – both types of s-wave resonances, with very low (e.g. at 2.762, 3.749, 4.738, 14.48 keV) and very high (6.788, 9.735, 10.712 keV) neutron widths are higher in the present experiment. There is no clear correlation with the neutron width, however, since other resonances in both categories agree reasonably well.

Due to the very large s-wave strength function of ^{144}Nd , the cross section is dominated by resonances with $\sigma_n \geq 10$ eV. Therefore, the prompt neutron sensitivity of the experimental setup has to be carefully considered. In the present analysis, this problem

is controlled in three ways: (i) Due to the short primary neutron flight path of 78 cm and the additional 10 cm distance between the sample and the individual modules of the 4π BaF₂ detector, background from scattered neutrons is spread out over a large TOF interval that is delayed compared to the prompt γ -signal from the respective resonance. (ii) The probability for capturing a neutron immediately after scattering is properly considered by the FANAC code. (iii) Any differences in the capture γ -ray spectra of individual resonances, that are difficult to consider in experiments using the pulse height weighting technique, are automatically accounted for in the 4π detector.

This is illustrated by the γ -spectrum of capture events in ¹⁴⁴Nd (Fig. 3) that was determined for the neutron energy range from 10 to 20 keV, where the cross section is dominated by broad s-wave resonances. The data of one of the experimental runs are plotted together with the respective spectrum of the ²⁰⁸Pb scattering sample, demonstrating the reliability of the background correction for scattered neutrons. In addition to the scattering correction, which eliminates the pronounced peak around channel #107 due to captures in the odd Ba isotopes of the scintillator, the correction for isotopic impurities accounts for capture events in ¹⁴³Nd and ¹⁴⁵Nd, which are otherwise expected as a common line at channel \sim #90 .

Table 2: Areas of capture resonances in ¹⁴²Nd

Resonance energy (keV)		g	l	g, n^1 (meV)	Resonance Area ² (meV)			
Ref. [11]	This Work				This Work	Ref. [5]	Ref. [11]	Ref. [13]
3.271	3.277	1	1	64	24.6 ± 2.7	15	25.1	16.9
3.382	3.391	...	0	343	56.0 ± 4.8	38	38.2	37.5
3.996	3.993	...	0	828	51.9 ± 5.2	47	45.6	42.5
4.145	4.142	1	1	85	20.0 ± 3.1	22	28.5	25.8
4.510	...	1	1	27	...	1.8	13.0	1.7
4.532	4.540	...	0	7572	49.5 ± 6.6	44	42.5	46.4
5.063	5.054	2	1	78	39.4 ± 2.6	40	41.1	37.2
5.156	5.152	2	1	90	38.7 ± 2.4	47	44.3	50.1
5.426	5.414	2	1	98	50.8 ± 2.7	50	45.9	57.1
5.491	5.475 ³	...	0	3305	50.7 ± 5.1	41	39.6	36.2
5.958	5.951 ³	1	1	38	7.9 ⁵	3.7	17.9	7.5
5.982	5.965	...	0	1437	45.5 ± 4.6	44	42.6	65.1
6.236	6.225	2	1	122	51.0 ± 3.0	58	50.9	58.0
6.927	6.905	...	0	575	69.5 ± 7.5	47	45.8	57.7
6.955	6.935 ³	1	1	72	23.3 ± 4.8	18	26.6	20.4
7.246	7.217	...	0	548	50.6 ± 4.2	45	43.8	45.6
...	7.627	...	0	600 ⁴	82.1 ± 4.9	...	...	61.2
8.261	8.231	...	0	533	39.4 ± 2.2	32	31.0	40.3
8.423	8.392	...	0	1944	51.5 ± 2.6	45	43.5	47.5
8.806	8.767	2	1	284	71.2 ± 2.0	64	56.6	65.6
9.019	8.974	...	0	192	123.8 ± 2.7	47	53.3	55.6
9.840	9.793 ³	2	1	290	59.1 ± 5.6	70	61.6	72.9

Table 2 (continued)

Resonance energy (keV)		g	l	g, n^1 (meV)	Resonance Area ² (meV)			
Ref. [11]	This Work				This Work	Ref. [5]	Ref. [11]	Ref. [13]
9.885	9.841 ³	...	0	11840	84.1 ± 8.9	64	61.9	70.1
10.15	10.11	2	1	540	84.2 ± 3.9	78	70.9	89.3
10.30	10.24 ³	1	1	66	30.6 ± 3.3	16	25.1	23.4
10.96	10.91	...	0	10540	51.6 ± 5.0	43	41.6	52.4
11.14	11.09 ³	2	1	90	51.4 ± 3.4	46	43.8	47.1
11.26	11.20 ³	1	1	109	31.9 ± 3.4	27	31.1	36.6
11.49	11.42	1	1	210	39.6 ± 3.6	36	36.4	37.3
12.94	12.86	2	1	526	86.4 ± 6.3	84	75.9	108.8
13.45	13.37 ³	2	1	96	59.9 ± 5.7	49	45.4	67.6
13.52	13.46 ³	...	0	4282	98.4 ± 16.5	84	81.3	87.6
13.66	13.58 ³	...	0	89450	134 ± 16	234	226.2	200.0
14.27	14.18	1	1	190	46.4 ± 6.3	35	35.8	34.6
14.49	14.40	2	1	112	60.5 ± 5.6	55	48.9	68.9
14.99	14.93 ³	1	1	52	10.4 ⁵	10	22.5	13.5
15.07	14.98	2	1	174	68.6 ± 6.4	68	58.4	66.6
15.46	15.36 ³	...	0	12890	43.2 ± 4.4	43	41.6	63.0
15.66	15.56	2	1	106	67.1 ± 3.2	53	47.7	62.1
15.94	15.83	2	1	254	68.6 ± 3.6	87	75.0	68.9
16.26	16.15 ³	...	0	54290	56.1 ± 7.6	91	88.0	...
16.36	16.25 ³	2	1	346	70.1 ± 5.6	82	72.3	...
17.07	16.96	2	1	1360	76.2 ± 3.8	89	83.5	...
17.36	17.24	2	1	114	61.8 ± 3.5	56	49.6	...
18.09	17.95	1	1	351	45.3 ± 4.8	40	39.3	...
19.09	18.95 ³	2	1	280	76.3 ± 5.5	77	67.2	...
19.27	19.13 ³	1	1	103	16.7 ± 9.2	26	30.5	...
19.37	19.23 ³	...	0	46580	77.2 ± 13.8	78	77.7	...
19.63	19.48 ³	1	1	78	5.7 ± 4.2	20	27.8	...
19.96	19.81 ³	2	1	106	52.8 ± 4.1	53	47.7	...
20.23	20.08 ³	2	1	212	89.9 ± 4.7	100	87.4	...
20.48	20.41 ³	2	1	144	81.2 ± 4.4	50	46.0	...
20.66	...	...	...	...	...	70	60.2	...
20.83	20.71 ³	1	1	85	25.7 ± 4.1	21	27.9	...
20.90	...	...	...	...	...	23	29.0	...

¹Values for g , l , and g, n adopted from the JENDL-3 evaluation.² $A_{\gamma} = g, n, \gamma / (g, n + \gamma)$.³Resonance energy was taken as fixed parameter.⁴Adopted value.⁵Adopted as fixed parameter from Ref. [13].

Figure 1: The neutron capture yield of ^{142}Nd and the corresponding FANAC fit.

Figure 2: The neutron capture yield of ^{144}Nd and the corresponding FANAC fit.

Table 3: Areas of capture resonances in ^{144}Nd

Resonance energy (keV)		g	l	g, n^1 (meV)	Resonance Area ² (meV)			
Ref. [11]	This Work				This Work	Ref. [5]	Ref. [11] ³	Ref. [13]
2.762	2.776	...	0	4091	111.0 ± 7.9	63	61.0	65.2
2.955	2.958	1	1	60	24.9 ± 2.1	13.5	24.4	24.5
3.063	...	1	1	44	...	3.0	21.2	5.6
3.293	...	1	1	45	...	4.2	21.5	6.6
3.538	3.553	...	0	15940	45.6 ± 9.1	43	41.6	61.2
3.631	...	1	1	42	...	1.0	20.7	...
...	3.677	1	1	84 ⁴	24.4 ± 3.2	...	...	...
3.749	3.752 ⁵	...	0	1386	47.1 ± 10.3	26	25.1	29.9
3.762	3.766	1	1	55	28.2 ± 5.6	11	23.5	26.8
4.239	4.240	1	1	54	28.8 ± 3.2	10	23.2	15.1
4.598	4.611	1	1	130	42.9 ± 3.6	29	31.1	45.1
4.738	4.748	...	0	305	79.1 ± 9.5	28	27.3	39.7
4.929	4.937 ⁵	...	0	24370	83.2 ± 12.6	67	64.8	75.1
4.954	4.962 ⁵	1	1	207	49.4 ± 8.1	34	34.2	57.6
5.147	5.148	1	1	74	35.6 ± 3.3	19	26.4	31.6
5.648	5.660	...	0	3398	68.0 ± 10.9	39	37.7	54.6
5.843	5.862	1	1	85	67.7 ± 6.2	22	27.7	39.5
6.106	6.106 ⁵	...	0	13530	85.9 ± 18.6	62	59.9	72.0
6.138	6.127 ⁵	1	1	100	36.2 ± 10.5	25	29.0	39.7
6.747	6.730 ⁵	1	1	74	25.7 ± 7.6	19	26.4	24.6
6.778	6.778 ⁵	2	1	116	47.3 ⁶	55	48.1	50.0
6.788	6.788 ⁵	...	0	48300	94.7 ± 22.1	45	43.6	37.6
7.017	7.021 ⁵	2	1	71	59.6 ± 10.9	36	38.1	55.9
7.048	7.053 ⁵	...	0	3477	64.0 ± 16.6	35	33.9	49.3
7.173	7.178	1	1	63	33.5 ± 5.5	15	24.9	23.2
7.400	7.398	1	1	140	63.8 ± 3.3	30	31.7	46.7
7.473	7.510 ⁵	...	0	5195	50.1 ± 5.4	36	34.8	52.9
7.812	7.815	1	1	94	53.0 ± 2.8	24	28.6	45.3
7.960	7.944	1	1	57	28.7 ± 3.4	12	23.9	21.8
8.186	8.190 ⁵	...	0	14370	98.3 ± 10.0	55	53.2	71.8
8.226	8.223 ⁵	1	1	81	12.8 ± 6.1	21	27.2	26.7
8.401	8.403	1	1	100	44.9 ± 3.1	25	29.1	37.5
8.846	8.847 ⁵	...	0	3138	53.3 ± 14.3	39	37.7	49.6
8.857	8.865 ⁵	1	1	85	49.8 ⁶	22	27.7	50.7
9.115	9.118	1	1	120	64.3 ± 9.0	28	30.6	41.5
9.239	9.236 ⁵	1	1	89	22.4 ⁶	23	28.1	27.5
9.296	...	1	1	52	...	9	22.9	6.3
9.342	9.330 ⁵	1	1	106	47.6 ± 15.1	26	29.6	38.9
9.372	9.368 ⁵	...	0	36290	45.6 ± 15.0	36	34.8	35.2
9.530	9.544	1	1	61	91.2 ± 9.5	14	24.6	38.2
9.557	...	2	1	66	...	32	36.5	32.2
9.735	9.740	...	0	47930	105.4 ± 17.1	77	74.5	62.6

Table 3 (continued)

Resonance energy (keV)		g	l	g, n^1 (meV)	Resonance Area ² (meV)			
Ref. [11]	This Work				This Work	Ref. [5]	Ref. [11] ³	Ref. [13]
9.956	9.945 ⁵	1	1	133	82.9 ± 7.6	19	26.4	51.9
10.04	10.02 ⁵	1	1	64	48.5 ± 8.0	21	27.2	41.0
10.12	10.11 ⁵	2	1	150	126.5 ± 8.0	61	52.5	79.8
10.71	10.69 ⁵	2	1	66	55.8 ⁶	73	36.7	57.8
10.71	10.69 ⁵	...	0	58500	115.3 ± 12.2	46	44.5	72.9
11.24	11.25 ⁵	...	0	18590	117.2 ± 10.0	64	61.9	90.5
11.39	11.40 ⁵	2	1	120	79.7 ± 7.1	60	51.7	60.3
11.64	11.64 ⁵	...	0	15930	68.1 ± 11.5	31	29.9	67.3
11.72	11.73 ⁵	1	1	53	39.1 ± 7.9	33	23.6	37.1
...	12.07 ⁵	1	1	100 ⁴	48.5 ± 6.8	...	...	46.1
12.18	12.19 ⁵	...	0	4322	64.5 ± 9.8	...	...	55.5
...	12.45	1	1	120 ⁴	42.7 ± 7.9	...	...	52.1
...	12.65	1	1	120 ⁴	40.1 ± 7.4	...	...	40.2
...	13.14 ⁵	1	1	130 ⁴	27.6 ⁶	...	...	28.3
13.24	13.23 ⁵	...	0	61820	89.9 ± 14.7	...	...	86.5
...	13.38 ⁵	1	1	140 ⁴	109.3 ± 10.1	...	...	122.0 ⁷
13.58	13.56 ⁵	...	0	14180	123.8 ± 13.2	...	...	67.1
...	13.83 ⁵	1	1	150 ⁴	42.5 ± 8.4	...	...	49.2
14.00	13.98 ⁵	...	0	41000	92.1 ± 15.1	...	...	83.4
14.48	14.47	...	0	2917	104.5 ± 11.8	...	...	65.9
...	14.82 ⁵	1	1	150 ⁴	42.9 ⁶	...	...	44.8
...	15.00	1	1	184 ⁴	106.1 ± 9.4	...	...	103.2
15.24	15.25	...	0	2270	94.7 ± 9.3	...	...	89.4
...	15.50	2	1	185 ⁴	126.7 ± 9.2	...	...	138.8 ⁷
...	15.82	1	1	200 ⁴	113.5 ± 11.0	...	...	110.5 ⁷
...	16.18 ⁵	1	1	180 ⁴	78.0 ± 13.2	...	...	68.4
16.32	16.30 ⁵	...	0	58710	194.5 ± 22.8	...	...	218.7
16.72	16.70 ⁵	...	0	26200	93.8 ± 19.4	...	...	72.0
16.83	16.82 ⁵	...	0	33900	108.1 ± 20.5	...	...	128.5
...	17.33 ⁵	1	1	200 ⁴	84.2 ± 12.7	...	...	...
17.54	17.52 ⁵	...	0	10840	117.2 ± 15.0	...	...	...
...	17.57 ⁵	1	1	200 ⁴	82.3 ⁶	...	...	...
...	17.98 ⁵	1	1	210 ⁴	102.5 ± 12.2	...	...	...
18.19	18.18 ⁵	...	0	8432	146.1 ± 23.0	...	...	...
...	18.30 ⁵	1	1	220 ⁴	73.5 ± 16.6	...	...	...
18.43	18.50 ⁵	...	0	40830	177.6 ± 17.7	...	...	...
...	18.95	1	1	240 ⁴	98.0 ± 11.5	...	...	...
...	19.20	1	1	240 ⁴	102.7 ± 11.5	...	...	...
19.41	19.48 ⁵	...	0	28590	104.6 ± 18.2	...	...	...
...	19.63 ⁵	1	1	260 ⁴	88.5 ± 13.8	...	...	...

Table 3 (continued)

Resonance energy (keV)		g	l	g, n^1	Resonance Area ² (meV)			
Ref. [11]	This Work			(meV)	This Work	Ref. [5]	Ref. [11] ³	Ref. [13]
...	19.90	1	1	260 ⁴	104.3 ± 11.1	...	...	...

¹Values for g , l , and g, n adopted from the JENDL-3 evaluation.

² $A_{\gamma} = g, n, \gamma / (g, n + \gamma)$.

³Capture area of p-wave resonances calculated with an average capture width of 41 meV.

⁴Calculated according to Eq. [2], g and l arbitrarily set to unity.

⁵Resonance energy was taken as fixed parameter.

⁶Adopted as fixed parameter from Ref. [13].

⁷Sum of several resonances.

Figure 3: Sum energy spectra of capture events in the ¹⁴⁴Nd sample and in the ²⁰⁸Pb scattering sample illustrating the proper correction of background from scattered neutrons and from isotopic impurities. The data refer to the neutron energy range from 10 to 20 keV. The region marked by arrows was used for evaluating the ¹⁴⁴Nd cross section.

Table 4: Averaged capture cross sections of ^{142}Nd and ^{144}Nd .

Neutron Energy (keV)	Capture cross section (mb) ¹					
	^{142}Nd			^{144}Nd		
	This Work	Ref. [2]	Ref. [13]	This Work	Ref. [2]	Ref. [13]
3–5	109.4 ± 5.5	$74.7 \pm 25.$ ²	90.8	$205.5 \pm 12.$	$255.9 \pm 35.$	186.6
5–7.5	118.7 ± 3.5	93.0 ± 9.0	121.6	$176.0 \pm 10.$	$207.8 \pm 14.$	149.5
7.5–10	96.6 ± 2.3	80.4 ± 5.3	77.5	158.9 ± 6.6	179.3 ± 8.1	120.8
10–12.5	44.8 ± 1.4	41.8 ± 3.4	44.2	120.6 ± 4.2	110.6 ± 4.8	90.8
12.5–15	68.2 ± 3.3	62.2 ± 2.6	70.9	93.3 ± 4.0	86.7 ± 3.5	78.4
15–20	34.6 ± 1.0	35.0 ± 1.3	...	99.2 ± 3.1	96.9 ± 1.7	...

¹Including statistical uncertainties

²This energy bin was not used in the evaluation of Maxwellian averaged cross sections in Ref. [2].

Table 5: Maxwellian averaged neutron capture cross sections of ^{142}Nd and ^{144}Nd .

Thermal Energy (keV)	$\langle \sigma v \rangle / v_T$ (mb) ¹					
	^{142}Nd			^{144}Nd		
	This Work	Ref. [2]	Ref. [15]	This Work	Ref. [2]	Ref. [15]
10	65.1 ± 1.9	60.1 ± 1.9	65.8 ± 2.9	147.0 ± 4.5	153.1 ± 4.5	122.2 ± 5.4
12	58.4 ± 1.6	54.4 ± 1.6	...	131.3 ± 3.6	135.8 ± 3.6	...
20	43.4 ± 0.9	41.5 ± 0.9	44.2 ± 3.0	98.9 ± 2.1	100.7 ± 2.1	86.7 ± 6.1
25	38.4 ± 0.8	37.1 ± 0.8	...	88.5 ± 1.7	89.6 ± 1.7	...
30	35.0 ± 0.7	34.0 ± 0.7	36.6 ± 3.0	81.3 ± 1.5	82.1 ± 1.5	73.2 ± 6.1

¹Total uncertainty, but without the 1.5% systematic uncertainty of the gold reference cross section.

4 Results

The average capture cross sections calculated from the resonance parameters listed in Tables 2 and 3 agree within the quoted statistical uncertainties with the previous analysis [2] (see Table 4). This confirms the proper treatment of the background due to scattered neutrons, which is comparably large at low energies. For two entries in Table 4 (^{142}Nd , 5-7.5 keV and 7.5-10 keV) the difference with the previous analysis reaches the 2σ level, but this occurs in regions with few resonances, where the large gaps between resonances were adding additional background to the first analysis.

For ^{142}Nd , excellent agreement is found with the data of Guber et al. [13]. The 25% difference in the interval from 7.5 to 10 keV is almost completely due to the s-

wave resonance at 9.019 keV which has a 2.2 times larger area according to the present experiment. In case of ^{144}Nd , however, there are systematic differences of up to 30% in the energy interval from 7.5 to 12.5 keV, a region where broad s-wave resonances are clearly dominating the cross section.

Based on the results of Table 4 revised Maxwellian averaged cross sections for thermal energies between 10 and 30 keV are given in Table 5 together with the previous results and the data of Ref. [15]. The differences between the first analysis and the present results are accounted for by the quoted uncertainties, which are now slightly smaller. The comparison with the cross sections of Guber et al. shows the same picture as for the average cross sections: perfect agreement for ^{142}Nd , but a significant discrepancy for ^{144}Nd at low thermal energies, due to the problem with the s-wave resonances below 12.5 keV.

5 Conclusions

The improved analysis of the neutron capture cross sections of ^{142}Nd and ^{144}Nd in the energy range from 2.8 to 20 keV yielded the resonance areas of 52 and 78 resonances, respectively. The resulting averaged cross sections are in good agreement with the first analysis which was based on the observed capture yields only [2]. This agreement confirms the reliable background subtraction in experiments with the Karlsruhe 4π BaF₂ detector as well as the correct treatment of multiple scattering and self-shielding effects in the two evaluations. The Maxwellian averaged cross sections could be slightly improved for low kT values but remain essentially unchanged. Therefore, the s-process studies based on the cross sections of Ref. [2, 16] are not affected.

6 Acknowledgments

The help of F.H. Fröhner in using the FANAC code is gratefully appreciated.

References

- [1] Z.Y. Bao and F. Käppeler, *Atomic Data and Nuclear Data Tables* **36**, 411 (1987).
- [2] K. Wisshak, F. Voss, F. Käppeler, L. Kazakov, and G. Reffo, report FZKA-5967, Forschungszentrum Karlsruhe (1997)
- [3] F. Voss, K. Wisshak, and F. Käppeler, *Phys. Rev. C* **52**, 1102 (1995).
- [4] K. Wisshak, F. Voss, and F. Käppeler, *Phys. Rev. C* **54**, 2732 (1996).
- [5] J.F. Mughabghab, M. Divadeenam, and N.E. Holden, in *Neutron Cross Sections, Vol. 1 Part A* (Academic Press, New York, 1984).
- [6] F. Käppeler, R. Gallino, M. Busso, G. Picchio, and C. Raiteri, *Astrophys. J.* **354**, 630 (1990).
- [7] O. Straniero, R. Gallino, M. Busso, A. Chieffi, C. Raiteri, M. Limongi, and M. Salaris, *Astrophys. J.* **440**, L85 (1995).
- [8] R.B. Firestone, V.S. Shirley, C.M. Baglin, S.Y.F. Chu, and J. Zipkin, *Table of Isotopes, 8th edition*, (Wiley, New York 1996).
- [9] K. Wisshak, K. Guber, F. Käppeler, J. Krisch, H. Müller, G. Rupp, and F. Voss, *Nucl. Instrum. Meth. Ser. A* **292**, 595 (1990).
- [10] F. H. Fröhner, report KfK-2145, Kernforschungszentrum Karlsruhe (1977).
- [11] Japanese evaluated nuclear data library JENDL-3 as obtained via internet from Brookhaven Nuclear Data Center 1997.
- [12] F.H. Fröhner, report GA-8380, Gulf General Atomic, 1968.
- [13] K.H. Guber private communications 1997
- [14] A.R. de L. Musgrove, B.J. Allen, J.W. Boldeman, and R.L. Macklin, *Proc. Int. Conf. Neutron Physics and Nuclear data for Reactors and other Applied Purposes*. Harwell, UK, 1978, p449. and report AAEC/E401 Australian Atomic Energy Commission (1976).
- [15] K.H. Guber, R.R. Spencer, P.E. Koehler, and R.R. Winters, *Phys. Rev. Lett.* **78**, 2704 (1997).
- [16] K. Wisshak, F. Voss, F. Käppeler, and L. Kazakov, *Proc. Int. Conf. Nuclei in the Cosmos 96*, Notre Dame (1996) to be published.