NEUTRON ACTIVATION CROSS SECTIONS ON Nd ISOTOPES AT 14.8 MeV

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Neutron activation cross sections for $(n, 2n)$, (n, p) and (n, α) reactions on Nd isotopes at 14.8 MeV have been measured using the Ge(Li γ-ray spectroscopy method. Totally, fourteen experimental data points have been obtained and three of them have been measured for the first time. The whole experiment has been controlled by the computer via the CAMAC system. The time variation of the neutron flux and the coincidence summing effects have been explicitly taken into account. The results obtained are discussed in detail and are compared with existing data.

ПОПЕРЕЧНЫЕ СЕЧЕНИЯ РАССЕЯНИЯ НЕЙТРОНОВ НА ИЗОТОПАХ Nd ПРИ ЭНЕРГИИ 14.8 МэВ

При помощи Ge(Li)-спектрометра измерены поперечные сечения нейтронной активации изотопов Nd для реакций $(n, 2n)$, (n, p) и (n, α) при енергии 14.8 МэВ. В общем измерено 14 сечений, причем 3 из них измерены впервые. Управление экспериментом проводилось при помощи ЭВМ в рамках системы КАМАК. Учтены поправки на временное изменение нейтронного потока и суммирование каскадных γ-квантов. Проведен детальный анализ полученных данных и их сравнение с данными других авторов.

I. INTRODUCTION

Recent compilations [1, 2] of experimental data concerning neutron activation cross sections (NACS) at 14 MeV have shown that the rections n + Nd leading to the emission of charged particles have been little investigated and that some data are missing at all: σ_{np}^{m} on ^{142}Nd, σ_{np} on ^{144,145,150}Nd and $\sigma_{n\alpha}$ on ^{150}Nd. The situation in the case of NACS of the type σ_{n2n} is the reverse. Relatively many experimental data have been published but they differ by an amount often exceeding the quoted errors [2]. Only few data have been measured by a modern Ge(Li) γ-ray spectroscopy technique. The last point seems to be rather important because the decay schemes of n + Nd reaction products are quite complicated [3—5]. From the

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theoretical point of view, σ_{np} cross sections for the long Nd isotopic chain are especially interesting. These would provide the possibility to test preequilibrium models of nuclear reactions mainly from the point of view of the σ_{np} dependence on $(N-Z)$. This possibility follows from the fact that the energy region of the primary proton spectra contributing to σ_{np} NACS contains a marked component of the preequilibrium decay.

We considered it therefore worthwhile to measure NACS on Nd isotopes in an effort to obtain new and to supplement existing experimental data using isotopically enriched as well as natural samples, Ge(Li) γ-spectroscopy and an improved measurement technique with the aim to reduce systematic errors and to increase the reliability of the data.

II. EXPERIMENTAL TECHNIQUE

II.1 Sample preparation

All samples used have been prepared by pressing Nd_2O_3 powder into plexiglass containers (Ø 16 mm). After weighing they were closed and sealed in order to prevent the air moisture to get inside. The isotopic abundances of the used Nd samples are given in Table 1. The different isotopic enrichment has served to suppress the interference reactions and to check the consistency of the measurements. All samples were of a spectral purity. The sample thickness varied from 200 to 400 mg/cm^2 and was chosen by taking into account the magnitude of the expected cross section, the selfabsorption corrections of low-energy γ-rays in the sample, and the neutron yield.

Table 1
Isotopic abundances (%) of samples

Samples	Isotope						
	142	143	144	145	146	148	150
Natural Nd	27.11	12.17	23.85	8.30	17.22	5.73	5.62
^{143}Nd	1.41	83.5	12.91	1.22	0.82	0.08	0.06
^{145}Nd	0.48	0.36	2.91	87.1	8.88	0.19	0.08
^{148}Nd	1.21	0.84	1.55	0.55	1.58	93.2	1.07
^{150}Nd	0.97	0.76	1.58	0.61	1.41	0.67	94.0

II.2 Irradiation, data acquisition and reduction

The samples have been irradiated by 14.8 MeV neutrons produced in T(d, n) ^{4}He reactions. D$^+$ ions have been accelerated in a small Cockcroft-Walton accelerator. A TiT target on Cu backing has been used and it has been directly cooled at the back by water. The geometry of irradiation has been carefully checked. The sample — TiT target distance has been 5 mm and the neutron energy spread has been estimated to be ±250 keV [6]. The maximum neutron yield was $\sim 3 \times 10^{10}$ n/s. With respect to a large assortment of reaction products half-lives and a relatively strong variation of the neutron yield it has been necessary to monitor the neutron flux. This has been performed by two monitors. The one (PR—M) registered recoil protons from a polyethylene radiator with a CsI scintillator (thickness 1 mm) and the second (Li—M) detected thermalized neutrons using Li-glass. The Li-scintillator was covered by a Pb layer (20 mm thick) and immersed in a paraffin cylinder (Ø 300 × 300 mm). The response functions of both monitors are displayed in Fig. 1. Their shape makes perfect discrimination possible

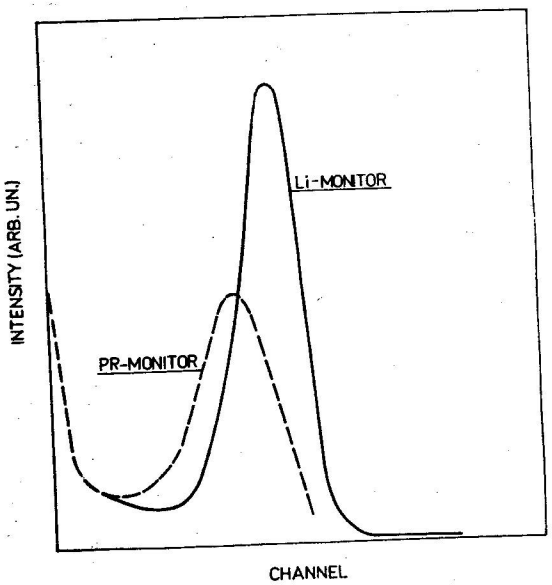

Fig. 1. Response functions of neutron flux monitors.

and small gain variations have a negligible effect on monitoring. Both monitors have been several times calibrated before each run using ^{27}Al (n, p) [7] and ^{56}Fe (n, p) [8] reactions. From all these measurements the average values of the calibration coefficients were calculated. Their error was ≤4 %. All NACS were then determined with the help of absolutely calibrated monitors and the time variations of the neutron flux have been explicitely taken into account.

The γ-ray spectra of the reaction products have been measured by a Ge(Li) detector (close-ended coaxial, 50 cm^3, $\Delta E = 2.5$ keV) in close geometry (samples were put on the detector's cover). The detector was absolutely calibrated for the geometry used [9] so that the coincidence summing effects [10] could be taken into account.

The whole experiment has been controlled by the TPA-70 minicomputer using the CAMAC system. The γ-ray spectra acquisition has been accomplished by a ND 4420 multichannel analyser connected to the system through the CAMAC—CAMAC LINK [11]. The control program has been written in FORTRAN and subroutines for communication with the CAMAC in real time have been used [12].

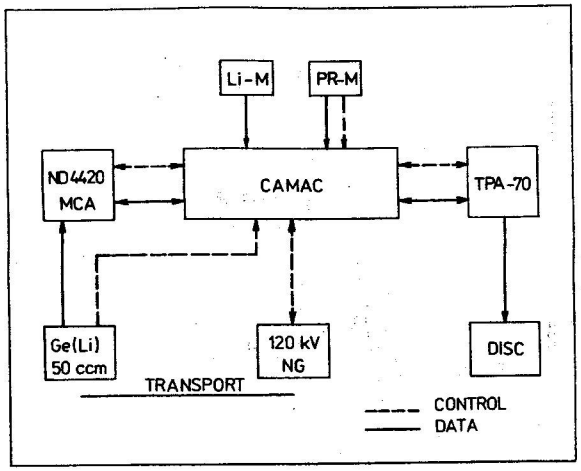

Fig. 2. Simplified block diagram of the Nd + n experiment.

Irradiated samples have been transported to the detector by a PIKO train ($\Delta t \approx 20$ s) and in the case of 150 Nd (n, p) ^{150}Pr ($T_{1/2} = 6.1$ s) the fast pneumatic transport ($\Delta t \approx 1$ s) has been used.

The measured data have been processed off-line on a TPA-70. The γ-ray spectra have been analysed by the GWENN code [13] based on a nonlinear least square fit to the semiempirical peak shape function similar to that used in [14]. The extracted areas of the full energy peaks (FEP) have been corrected for coincidence summing, using the KORSUM code [10] and selfabsorption of γ-radiation in the sample [15]. The uncertainty of FEP detection efficiency was ≤ 1.5 % from 60 to 2000 keV [9].

The activation cross sections have been calculated according to the relation

$$\sigma_g = \frac{\sigma_m \lambda_m I_T}{\lambda_g - \lambda_m} + \frac{e^{\lambda_g (T_0 + T_v)}}{\{1 - e^{-\lambda_g T_M}\} \int_0^{T_0} e^{\lambda_g t} \Phi(t)\, dt} \times$$

$$\times \left\{ k \frac{P_\gamma A}{\varepsilon_\gamma I_\gamma \eta G} - \frac{\sigma_m \lambda_m I_T}{\lambda_g - \lambda_m} e^{-\lambda_m (T_0 + T_v)} [1 - e^{-\lambda_m T_M}] \times \right.$$

$$\left. \times \int_0^{T_0} e^{\lambda_m t} \Phi(t)\, dt \right\}, \qquad (1)$$

where σ_m, σ_g, λ_m, λ_g are cross sections and decay constants of the metastable and the ground state, resp.: T_0, T_v, T_M are irradiation, cooling and measurement times; I_T, I_γ are the absolute intensities of the isomeric and the measured γ-transition, resp.; ε_γ, P_γ are the absolute FEP efficiency and FEP area; A, η, G are the atomic weight, isotopic abundance and sample weight, resp.; Φ is the relative neutron flux and k is the calibration coefficient of a monitor. In cases when the isomeric transition could not be measured (hence σ_m), the quantities σ_m and σ_g were determined from the decomposition of a ground state decay curve. The decay constants were taken from [6].

III. RESULTS AND DISCUSSION

III.1 The $(n, 2n)$ reactions

At first sight one expects that $(n, 2n)$ NACS should be known with a good precision due to their magnitude ($\sim$1b) and the different experimental results should not differ too much. However, as shown, e.g., in [2], the situation is not like that and we consider it worthwhile to present and discuss some specific problems. Unlike in other papers using γ-ray spectroscopy to determine NACS we have always used (whenever possible) several γ-transitions of the reaction products. This randered it possible to check the consistency of the published I_γ [3—5], which apparently influence in a decisive way the values of cross sections. In many cases, however, neither this approach allows to prefer unambiguously some of the σ_{n2n} values obtained.

^{142}Nd $(n, 2n)$ ^{141m,g}Nd reaction

The isomeric cross section σ_m has been determined by measurement of the 756 keV isomeric transition (IT). The values of I_γ [3—5] are mutually consistent, as are the values of σ_m reported by other authors (see Tab. 2). Our $\sigma_m = (756 \pm 70)$ mb is in agreement with other data within the errors quoted.

In the case of σ_g we have used three γ-transitions: 145.4, 1226.7 and 1292.5 keV. Using I_γ from [5] we have obtained $\sigma_g = (683 \pm 70)$ mb and I_γ from [4] lead to $\sigma_g = (778 \pm 73)$ mb (in ref. [3] only relative intensities are given). Though both values are compatible with each other, we have adopted the second due to a smaller dispersion between the different lines used. We emphasize that the magnitude of the errors quoted is a consequence of an averaging with respect to three lines used. For an individual line the error would be lower by about 3—4 %. The adopted value of σ_g can directly be compared with that of Prasad et al. [16]. These authors used the 1292.5 keV transition but with I_γ several times higher than that given in [4]. Recalculating their results with I_γ from [4] we have obtained σ_g ([16]) = 11.4b! On the other hand assuming an error of 10 in the quoted I_γ [16] and recalculating their σ_g with I_γ from [4], we have obtained σ_g ([16]) = 582 mb, which is an acceptable value though a little low.

Table 2

Details of $(n, 2n)$ cross section measurements and comparison with recent literature values

Reaction	Reaction product decay data			Adopted cross section (mb)	Literature values (mb)	Ref.
	$T_{1/2}$	E_γ (keV)	I_γ			
^{142}Nd $(n, 2n)$ ^{141m}Nd	62.4 s	756.5	0.915[b])	756 ± 70	673 ± 66	[20]
					591 ± 45	[17]
					628 ± 63	[16]
					709 ± 190	[21]
^{142}Nd $(n, 2n)$ ^{141g}Nd	2.49 h	145.4	0,0022[a])		1101 ± 165	[17]
		11.26.9	0.0075[a])	778 ± 73	1447 ± 210	[16]
		1292.6	0.0012[a])		1530 ± 190	[21]
				1544 ± 101*	1907 ± 146*	[22]
^{148}Nd $(n, 2n)$ ^{147}Nd	11.1 d	319.4	0.0205[b])		1950 ± 150	[17]
				1780 ± 50		
		531.0	0.133[b])		1626 ± 200	[16]
					1700 ± 142	[22]
^{150}Nd $(n, 2n)$ ^{149}Nd	1.73 h	114.3	0.16[c])		1906 ± 160	[17]
				1703 ± 82		
		211.3	0.23[c])		1728 ± 276	[20]
		654.8	0.084[c])		1652 ± 138	[22]

a) Ref. [4]
b) Ref. [5]
c) Ref. [3]
* $\sigma_m + \sigma_g$

In all other cases out σ_g is substantially lower than those given by authors quoted in Table 2. For σ_{n2n}^{m+g} we have obtained (1544 ± 101) mb. This value agrees, within

errors, with that given by Qaim [17] and is in reasonable agreement with the theoretical calculations based on statistical models [18].

^{148}Nd $(n, 2n)$ ^{147}Nd reaction

In order to determine the NACS of this reaction we have used the 319.4 and 531.0 keV transitions. The value of σ_{n2n} for different sets of I_γ have thus been: (2521 ± 194) mb [3], (1649 ± 73) mb [5] and (1780 ± 50) mb [4]. From the systematics of σ_{n2n} in the rare earth region it follows that the first value is too high and therefore I_γ [3] too low. We note that the difference in I_γ represents in this case ~300 mb. Since such a difference is the smallest for the last case, we adopted $\sigma_{n2n} = (1780 \pm 50)$ mb. Again this value can be compared with that given by Qaim [17] (91 keV, $I_\gamma = 0.286$) and Prasad et al. [16] (531 keV, $I_\gamma = 0.17$). Recalculating their results with I_γ from [4] we obtain σ_{n2n} ([17]) = (2065 ± 200) mb and σ_{n2n} ([16]) = (2303 ± 283) mb. We see that we are in agreement only with Qaim, though the comparison with original data shows — see Tab. 2 — mutual agreement. Such comparison is, however, hardly possible as long as input data for the calculations of NACS are not given.

We note that our value of σ_{n2n} is in good agreement with the theoretical calculations [18].

^{150}Nd $(n, 2n)$ ^{149}Nd reaction

In this case we used three γ-transitions for the determination of σ_{n2n}: 114.3, 211.3 and 654.8 keV. Using the three sets of I_γ [3—5] we have obtained σ_{n2n}, differing mutually by several hundred mb. The situation was further complicated by the fact that the line 654.8 keV implied substantially different σ_{n2n} values with respect to the first two lines for all three sets of I_γ: −300 mb [3], +160 mb [5]. We have assumed that I_γ (654.8 keV) was wrong in all three cases and was therefore disregarded. We have then obtained the following σ_{n2n} for given sets of I_γ: (1703 ± 82) mb [3], (1250 ± 65) mb [4] and (1442 ± 70) mb [5]. The differences in σ_{n2n} for the two lines were comparable in each case so that they helped to decide which value would be the more consistent. However, we have adopted the first value, having in mind the following supporting arguments.

Starting from the binding energies of the first and the second neutron one expects that σ_{n2n} (^{150}Nd) ≤ σ_{n2n} (^{148}Nd) as a consequence of a stronger preequilibrium emission of the primary neutron (higher excitation energy). This trend is further amplified by the competition of the $(n, 3n)$ reaction, which is stronger for ^{150}Nd (smaller separation energy of the third neutron). As the total energy difference is ~1 MeV, we expect also a small difference between σ_{n2n} for both isotopes. Also our adopted value is in good agreement with theoretical calculations [18].

Now we compare our value with values of other works using γ-spectroscopy. Qaim [17] has reported (1906 ± 160) mb for I_γ (211.3 keV) = 0.3416. Recalculating this value with I_γ from [3] we obtain (2831 ± 237), which is evidently too high a value. Menon and Cuypers [10] have used I_γ (654.8 keV) = 0,084 and they found $\sigma_{n2n} = (1728 \pm 276)$ mb, while our measurements for that line (which was not considered) implied $\sigma_{n2n} = (1400 \pm 65)$ mb.

From the discussion above we see that the published NACS σ_{n2n} data are considerably scattered which —unfortunately— lovers their physical and practical significance. As far as measurements utilizing Ge(Li) γ-ray spectroscopy are concerned we have tried to show that the uncertainty in I_γ markedly influences the published data. However, neither this fact can explain fully the existing differences.

Frehaut et al. [22] have measured σ^{tot}_{n2n} on Nd isotopes using the method which does not depend on the branching ratios for γ and β. Our values are in very good agreement with theirs for ^{148,150}Nd, but for ^{142}Nd our value is significantly lower. We feel, however, that with respect to σ_{n2n} (^{148}Nd) their σ_{n2n} (^{142}Nd) value — see Table 2 — is too high. The competition of $(n, 3n)$ — not possible for ^{142}Nd — lowers the corresponding cross section by about 150 mb [18]. On the other hand the separation energy of the second neutron (S_{n2}) for ^{142}Nd is about 2.5 MeV higher than S_{n2} for ^{148}Nd. Since $d\sigma/d\varepsilon_n$ is approximately 50—60 mb/MeV in the vicinity of S_{n2} for nuclei in this mass region [23], the difference in S_{n2} represents ~150 mb in favour of ^{142}Nd. Higher binding energy of the incoming neutron in ^{142}Nd (1.1MeV) makes the preequilibrium emission of the primary neutron stronger with respect to ^{148}Nd. We expect that $\sigma_{n2n}(^{142}Nd) \lesssim \sigma_{n2n}(^{148}Nd)$.

III.2The (n, p) reactions

The (n, p) reactions around ~14 MeV on Nd isotopes have not been studied thoroughly so far. Only four from nine activation cross sections are known, and only one of them has been measured by means of a Ge(Li) γ-spectroscopy (β-counting has been used in other cases). In our work six cross sections have been measured and three of them have been determined for the first time.

$$^{142}\text{Nd}\ (n, p)\ ^{142m,g}\text{Pr}$$

The total NACS of that reaction has been determined by means of the 1575.7 keV γ-line only, because the decay of ^{142}Pr feeds mainly (96.3 %) the ground state of ^{142}Nd [4]. Intensities from Refs. [3, 5] are in a good agreement and the total cross section obtained $\sigma^{tot}_{np} = (13.8 \pm 1.1)$ mb is in a good agreement with data of Refs. [21, 24] (see Table 3). If the intensities of Ref. [4] are used σ^{tot}_{np} increases by 3.2 mb. This value, however, cannot be a priori rejected. It is known that the nucleus ^{142}Pr possesses a metastable state ($J^\pi = 5^-$) with an energy of

3.7 keV above the ground state ($J^\pi = 2^-$). We have tried to determine σ^m and σ^g from the decay curve of the 1576 keV γ-line, but in the limit of the declared errors a statistically significant yield of σ^m has not been obtained. This result implies the fact that σ^m represents only a small fraction of σ^{tot} (we estimate its $\lesssim 5$ %).

Since feeding m- or g-state, respectively, by γ-transitions in the ^{142}Pr nucleus is controlled by the spin distribution of the excited levels, we may conclude that the primary proton takes away a substantial portion of the angular momentum of the composite nucleus and must be emitted with a mean energy greater than the Coulomb barrier (~7 MeV). This conclusion is in agreement with experimental facts showing that the emission of protons from a compound nucleus for heavier nuclei is not very probable [26].

$$^{143}\text{Nd}\ (n, p)\ ^{143}\text{Pr}$$

The decay of the ^{143}Pr nucleus feeds practically completely the ground state of ^{143}Nd. The intensity of the β^--transition to the 742 keV level represents only 1.2×10^{-4} %. We have used an isotopically enriched sample but this γ-transition has not been observed. The only existing datum measured by Coleman et al. [24] (β-counting) is given in Table 3.

$$^{144}\text{Nd}\ (n, p)\ ^{144m,g}\text{Pr}$$

NACS of this reaction have been measured for the first time. Both cross sections have been determined by an analysis of the decay curve of the 696.5 keV γ-line that is fed mainly by the β^- decay of ^{144,g}Pr. The influence of ^{144,m}Pr on feeding the 696.5 keV level is negligible. Intensities I_γ (696.5 keV) from Refs. [3, 5] are in a good agreement and corresponding cross sections are given in Table 3. I_γ [4] is smaller but the corresponding cross section agrees, in the framework of the given errors, with previous results. Since an isomeric transition (IT, 59 keV) is strongly converted and the efficiency of our detector in this energy region is small, the quantity σ^m could not be obtained by measuring IT.

$$^{145}\text{Nd}\ (n, p)\ ^{145}\text{Pr}$$

The cross section of this reaction has been measured for the first time. The γ-lines 475.8 and 748.3 keV have been used. Intensities I_γ [4, 5] are in agreement and the cross sections $\sigma_{np} = (8.2 \pm 2.2)$ mb. Intensities I_γ [3] are somewhat higher but more consistent with each other. Intensities I_γ [3] have, therefore, been used and the cross section $\sigma_{np} = (7.5 \pm 1.6)$ mb has been adopted.

$$^{146}\text{Nd}\ (n, p)\ ^{146}\text{Pr}$$

Table 3
Details of (n, p) cross section measurements and comparison with other literature values

Reaction	Reaction product decay data			Adopted cross section	Literature value	Ref.
	$T_{1/2}$	E_γ (keV)	I_γ	(mb)	(mb)	
^{142}Nd (n, p) ^{142}Pr	19.1 h	1575.7	0.037[b])	13.8 ± 1.1*	11.9 ± 0.9	[21]
					13.5 ± 2.7	[24]
^{143}Nd (n, p) ^{143}Pr	13.6 d	742.0	'10^{-6}[b])	not measured	11.5 ± 2.3	[24]
^{144}Nd (n, p) ^{144m}Pr	7.2 m	696.5	0.0148[b])	1.7 ± 0.6	none	
^{144}Nd (n, p) ^{144g}Pr	17.3 m			10.5 ± 2.3	none	
				12.2 ± 2.4*		
^{145}Nd (n, p) ^{145}Pr	5.98 h	675.8	0.0045[c])			
				7.5 ± 1.6	none	
		748.3	0.0047[c])			
^{146}Nd (n, p) ^{146}Pr	24.1 m	453.8	0.55[c])		4.7 ± 0.6	[19]
				4.7 ± 0.5		
		735.7	0.089[c])			
^{148}Nd (n, p) ^{148}Pr	2.28 m	301.7	0.91[b])	2.14 ± 0.17	3.5 ± 0.8	[25]

b) Ref. [5] c) Ref. [3]
* $\sigma_m + \sigma_g$

There was a serious problem to determine the cross section of this reaction. The γ-lines 453.8 and 135.7 keV have been used, but their intensities show great differences not only between different sources of intensities (Refs. [4, 5] vs. Ref. [3] but even the calculated cross sections σ_{np} show differences of 42 % (I_γ [4, 5] and 32 % (I_γ [3]) between γ-lines used from a given source of I_γ. We have decided, therefore, to determine σ_{np} as a mean value with intensities from Ref. [3]. The adopted cross section is $\sigma_{np} = (4.7 \pm 0.5)$ mb.

Our result is in a good agreement with results given by Cuzzocrea et al. [21] (β-counting) and by Qaim [19].

The latter, however, is only a random one, since Qaim used I_γ (453.8 keV) = 0.85, a value substantially higher than 0.55 [3]. Converting his result one obtains $\sigma_{np} = (7.3 \pm 0.9)$ mb, a value which is in strong disagreement with the result of Ref. [21] and our own result.

^{148}Nd (n, p) ^{148}Pr

The only NACS of this reaction has been measured by Wille and Fink [25] (β-counting). Their value is not obviously true, since they used $T_{1/2} \approx 12$ min., while the most recent results give $T_{1/2} \approx 2.3$ min [4, 5]. The 301.7 keV γ-line has been used for determining σ_{np}. The remaining γ-lines have not been used either

because of a strong interference of other reactions or a small area of FEP. Using $I_\gamma = 0.91$ [4, 5], we have obtained $\sigma_{np} = (2.14 \pm 0.17)$ mb.

^{150}Nd (n, p) ^{150}Pr

Although the decay characteristics of a recently discovered isotope ^{150}Pr [27] have not been sufficiently well known so far [27, 28], we have tried to identify a reaction product by a γ-line 130 keV. Due to a short half-life (6.1 s [27]) we have used a cyclic activation (irradiation 10 s, counting 10 s). A fast pneumatic transport system ($\Delta t \doteq 1.5$ s) has been used to transfer the sample. A 130 keV γ-line, however, has not been observed not even after 120 cycles. We have detected only strong γ-lines from the ^{150}Nd $(n, 2n)$ ^{149}Nd reaction.

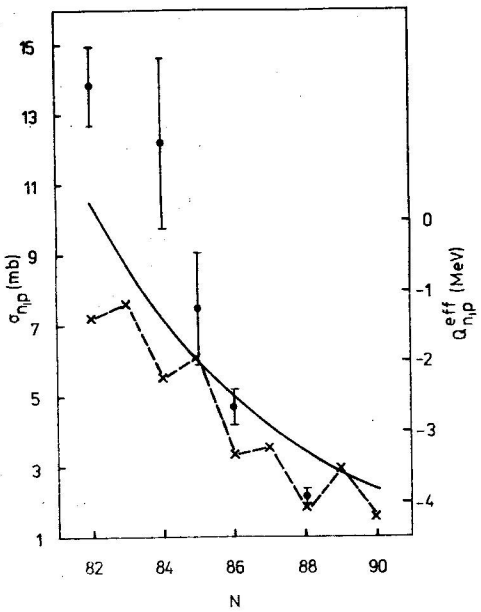

Fig. 3. Comparison of experimental values (points) with predictions of Levkovskii's formula (solid line) for (n, p) reactions on Nd isotopes. Q^{eff}_{np} values (dashed line) are also given.

The reason of our unsuccessful attempt is not obvious, since enrichment and neutron flux in our case have been practically the same as those used by Ward et al. [27]. One explanation may be a low peak: Compton ratio of our detector (16 : 1).

A comparison of our results with Levkovskii's semiempirical formula [29]

$$\sigma_{np} = 45 \,.\, 2\,(A^{1/3}+1)^2 \exp\{-33\,(N-Z)/A\}\ \text{(mb)} \qquad (2)$$

is shown in Fig. 3. This formula is, in principle, identical with a relation following from statistical theory [30].

An exponential slope σ_{np} in Eq. (2) is given mainly by an effective Q value of the reaction, $Q_{np}^{\text{eff}} = Q_{np} - \delta$ (dashed line in Fig. 3; pairing corrections δ have been from Ref. [31]. It is seen, however, that a theoretical slope is not so strong as experimental data indicate and therefore another mechanism has to be included. As mentioned above the contribution of a preequilibrium emission of protons for excitation energies ~20 MeV is dominant for heavier nuclei. Assuming that only a few nucleus of the target nucleus take part in the initial stages of a nuclear reaction [32], the probability of excitation of a proton may decrease with a increasing number of neutrons. This vact may qualitatively explain a stronger experimental slope σ_{np}^{exp} in a relation to Eq. (2). A more detailed theoretical analysis of this problem would be very worthwhile, but is not the aim of this work.

III.3 Reactions (n, α)

There were no problems to determine NACS in (n, α) reactions. Intensities I_γ from different sources [3—5] are in a very good agreement. Our resulting $\sigma_{n\alpha}$ values together with results of other authors are given in Table 4. One γ-line has been used to determine the reaction product in all cases.

Table 4

Details of (n, α) cross section measurements and comparison with other literature values. (I_γ are taken from Ref. [5]).

Reaction	Reaction product decay data			Adopted cross section	Literature value	Ref.
	$T_{1/2}$	E_γ (keV)	I_γ	(mb)	(mb)	
^{142}Nd (n, α) $^{139m+g}$Ce	137.5 d	165.8	0.789	6±0.9*	m: 2±2	[25]
					g: 10±2	[25]
^{144}Nd (n, α) ^{141}Ce	32.5 d	145.4	0.484	4.5±0.6	9.0±1.7	[16]
					15.5	[33]
^{146}Nd (n, α) ^{143}Ce	33.0 h	293.3	0.514	4.2±0.7	8.3±2.0	[25]
					2.6±0.4	[24]
					4.42±0.47	[34]
^{148}Nd (n, α) ^{145}Ce	3.0 m	724.3	0.69	2.4±0.2	5±1	[25]

* $\sigma_m + \sigma_g$

In the reaction ^{142}Nd (n, α) the metastable cross section σ^m could not be obtained, since the energy and lifetime of IT in the nucleus ^{139}Ce are practically the same as those of IT in the product of the reaction ^{142}Nd $(n, 2n)$. The latter reaction has, however, a cross section which is some hundred times higher. An analysis of the decay curve for IT (^{141m}Nd) has not been successful.

Note that our results, with the exception of $\sigma_{n\alpha}$ (^{146}Nd), are in a strong disagreement with other published experimental data. Wille and Fink [25] (β-counting) have measured $\sigma_{n\alpha}$ for the isotopes ^{142,146,148}Nd. Their results are almost exactly twice as high as ours. Regarding data for $\sigma_{n\alpha}$ (^{146}Nd) of other authors (Table 4) we are inclined to assume that a factor 2 is due to some systematic error in Ref. [25].

Prasad et al. [16] have measured $\sigma_{n\alpha}$ (^{144}Nd) by a similar technique. It is quite surprising that their $\sigma_{n\alpha}$ is twice as high as our value, although the same intensity I_γ was used in both cases. Our result cannot be influenced by the decay of ^{141}Nd ($E_\gamma = 145.4$ keV, $I_\gamma = 0.24$), since the cooling time for measuring the activity ^{141}Ce was roughly one hundred times as large as $T_{1/2}$ (^{141g}Nd). Since no measuring details for this reaction are given in Ref. [16], we cannot try to identify the cause of the mentioned discrepancy.

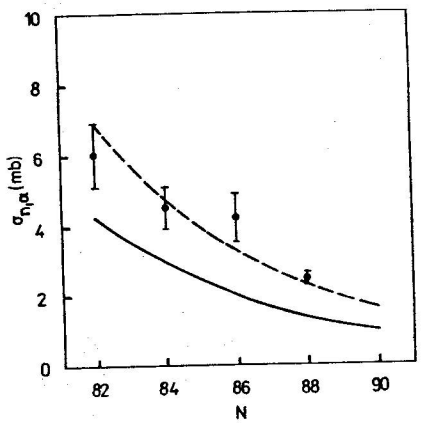

Fig. 4. Comparison of experimental values (points) with prediction of Levkovskii's formula (solid line) and multiplying this formula by a factor 1.65 (dashed line) for (n, α) reactions on Nd isotopes.

Our value of $\sigma_{n\alpha}$ for (^{146}Nd) is in a very good agreement with the value given by Sato et al. [34] (Ge(Li) γ-spectroscopy) and is higher by about 60 % than the value given by Coleman et al. [24] (β-counting).

In Fig. 4 a comparison of our results with predictions of Levkovskii's formula [35, 36]

$$\sigma_{n\alpha} = 0.4\ \sigma_{np}\ , \qquad (3)$$

is shown, where σ_{np} is given by Eq. (2).

Eq. (3) describes rather well the general trend of the experimental data and by multiplying Eq. (3) by a factor 1,65, the agreement in absolute values is also obtained. This agreement is surprising, since Eq. (3) is valid for $A<70$ [36].

Since the influence of preequilibrium α-emission in the rare earth region is dominant [37], it would be worthwhile to study the connection of Levkovskii's formula with precompound processes.

IV. SUMMARY

The aim of this work has been to measure NACS on Nd isotopes. Emphasis has been given to obtaining new data, remeasuring existing data, increasing the accuracy and reliability of data and to reducing systematic errors. Our aims, however, have only partially been realized.

Three cross sections have been obtained for the first time: σ_{np}^{mg} (^{144}Nd) and σ_{np} (^{145} Nd). The products of the reaction ^{150}Nd (n, p) and ^{150} Nd (n, α) have not been identified.

We have tried to increase the reliability of data and to reduce systematic errors by means of an automation of the measuring process, monitoring of the neutron flux, a careful calibration of the Ge(Li) detector in the geometry used, using more γ-lines for identifying reaction products to obtain NACS and applying corrections for coincidence summing effects and selfabsorption of γ-lines.

The comparison of our results with those of other authors shows a strong disagreement in some cases even for $(n, 2n)$ reactions having NACS values of the order of 1—2 b.

Where possible, we recalculated other results using our intensities, but in some cases, this led to even greater differences.

In measuring NACS by γ-spectroscopy of the reaction products, the uncertainties of input intensities are certainly a fundamental source of errors. However, as shown in our work, not the only one. On the other hand, the given set of intensities I_γ [3—5] cannot be valid if it does not imply the same value of NACS for various γ-lines of a given reaction product.

It would be worthwhile, therefore, to measure I_γ again with a greater accuracy.

Although the activation method is well known and, in principle, very simple, it seems to be worthwhile to study it again with an effort to identify some relevant source of systematic errors.

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REFERENCES

[1] *CINDA* 76/77, IAEA, June 1976.
CINDA 78, Supplement 1—5, IAEA 1978.
[2] Bychkov, V. M., et al.: *INDC (CCP)* — 146/LJ, IAEA, 1980.
[3] *Atomic Data and Nucl. Data Tables*, 13, (1974), Nos. 2—3.
[4] *Table of Isotopes*, 7th edition. Ed. by Lederer, C. M., Shirley, V. S.: John Wiley and Sons, Inc., New York, 1978.
[5] Reus, U., et al.: *Gamma-ray catalog, GSI-Report 79-2*, Darmstadt, Februar 1979.
[6] Paulsen, A., Liskien, H.: Nucl. Data Tables *11* (1973), 569.
[7] Jarjis, R. A.: J. Phys. G *4* (1978), 445.
[8] Ryves, T. B., et al.: Metrologia *14* (1978), 127.
[9] Gmuca, Š., Ribanský, I.: Nucl. Instr. Meth. *accepted for publication.*
[10] Debertin, K., Schötzig, U.: Nucl. Instr. Meth. *158* (1979), 471.
[11] Horváth, P., et al. *IXth Int. Symp. on Nucl. Electronics*, D 13-11182, Dubna 1978, 356.
[12] Morháč, M., Gmuca, Š.: *to be published.*
[13] Gmuca, Š., Ribanský, I.: *to be published.*
[14] Phillips, G. W., Marlow, K. W.: Nucl. Instr. Meth. *137* (1976), 525.
[15] Nemets, O. F., Gofman, Yu. V.: *Handbook on Nuclear Physics*, Naukova Dumka, Kiev 1975.
[16] Prasad, R., et al.: Nucl. Phys. A *125* (1969), 57.
[17] Qaim, S. M.: Nucl. Phys. A *224* (1974), 319.
[18] Kumabe, I.: J. Nucl. Sci. Techn. *14* (1977), 460.
[19] Qaim, S. M.: Radiochem. Radioanal. Lett. *25* (1976), 335.
[20] Menon, M. P., Cuypers, M. Y.: Phys. Rev. *156* (1967), 1340.
[21] Cuzzocrea, P., et al.: Nuovo Cim. *52 B* (1967), 476.
[22] Frehaut, J., et al.: *Proc. of Symp. on Neutron Cross Sections from 10—50 MeV*, Upton USA, May 1980.
[23] Hermsdorf, et al.: *Report ZfK—277 (U).* Rosendorf 1977.
[24] Coleman, R. F., et al.: Proc. Phys. Soc. *73* (1959), 215.
[25] Wille, R. G., Fink, R. W.: Phys. Rev. *118* (1960), 242.
[26] Braga-Marcazzan, G. M., et al.: Phys. Rev. *C 6* (1972), 1398.
[27] Ward, T. E., et al.: Phys. Rev. *C 2* (1970), 2410.
[28] Skarnemark, G., et al.: Radiochimica Acta *23* (1976), 98.
[29] Levkovskij, V. N.: Sov. Phys. JETP *18* (1978), 944.
[30] Pai, M. L., Andrews, D. G.: Can. J. Phys. *56* (1978), 944.
[31] Nemirovsky, P. E., Adamchuk, Yu. V.: Nucl. Phys. *39* (1962), 551.
[32] Gmuca, Š., Ribanský, I.: *Proc. 2nd Int. Symp. on Neutron Induced Reactions*, Smolenice 1979, 155.
[33] Havlík, E.: Acta phys. Austriaca *34* (1971), 209.
[34] Sato, T., et al.: Nucl. Sci Technol. *12* (1975), 681.
[35] Levkovskij, V. N.: Sov. J. Nucl. Phys. *18* (1974), 361.
[36] Pai, H. L., Andrews, D. G.: Can J. Phys *57* (1979), 703.
[37] Ribanský, I., Gmuca, Š.: *Proc. 2nd Int. Symp. on Neutron Induced Reactions*, Smolenice 1979, 221.

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