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THE PROBABILITY OF SINGLE-NUCLEON EMISSION IN π^- CAPTURE REACTIONS ON THE ^{152}Sm AND ^{164}Dy NUCLEI

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1. INTRODUCTION

In recent years the problem of the probability of negative pion absorption followed by the emission of one proton or neutron has been widely discussed. There are at least three factors which are of great interest in this connection.

First of all, the process of the single-nucleon absorption of negative pions can be a tool for clarifying the role of the high-momentum component of the nuclear wave function.

This reaction can also be used to study the single-hole states in residual nuclei.

However, the interest shown in this reaction is mainly associated with the problem of the existence of π-condensation [1] and Δ-isobars [2] in atomic nuclei. Assumptions are advanced that the physical consequence of the phase transition due to the reconstruction of the pion field, can be the existence of a substance with a density close to the nuclear one and consisting of the heavier baryons than nucleon isobars, strange particles, etc.

At present there exist two approaches to the study of the probability of single-nucleon absorption of negative pions.

The first approach is based on the study of the high-energy part of the inclusive neutron spectra of the reaction (π^-,n) [3]. It should be noted that such a method is applicable only to light nuclei such as ^6Li, ^7Li and possibly ^{12}C (ref. [3]).

The second method involves the detection of the γ-radiation of β-active residual nuclei produced in the slow π^--induced reactions [4-7]. This seems to be the only way of studying the probability of single-nucleon absorption of π^- in heavy nuclei. This technique allows one to separate the final channel of the reaction (π^-,p) or (π^-,n) from other background reactions of the type $(\pi^-;yp,xn)$. However, in this case it is impossible to separate the reaction channels involving non-radiative (π^-,n) and (π^-,p), and radiative $(\pi^-,\gamma n)$ and $(\pi^-,\gamma p)$ pion captures. Thus the values measured will constitute the upper limits of each of these two processes.

The simultaneous study of the two channels of the reactions (π^-,p) and (π^-,n) on the same target nucleus is of special interest.

In the present paper the cross sections of the channels (π^-,p) and (π^-,n) were estimated using targets manufactured of the monoisotope ^{152}Sm oxide with an enrichment of up to 99% and of Sm from the natural isotopic mixture. The stable isotope ^{152}Sm is a unique one to observe the reactions $^{152}Sm(\pi^-,p)^{151}Nd$ and $^{152}Sm(\pi^-,n)^{151}Pm$. For the comparison of the probability of the channel (π^-,n) the reaction $^{164}Dy(\pi^-,n)^{163}Tb$ has been investigated.

2. EXPERIMENTAL TECHNIQUE

An experiment has been carried out using a pion beam from the JINR Synchrocyclotron. Pions with an energy of 30 MeV were focussed into the targets under study by a wide-angle solenoidal lens. To provide protection against neutron background and to achieve the maximum density of pion stops in the target substance, the targets were placed into a capsule made of cadmium-clad borated polyethylene. The pions retarded in the cadmium and polyethylene layers stopped in the targets. The density of pion stops was equal to $4 \times 10^5 g^{-1} \cdot s^{-1}$.

The total number of pion stops in the target was measured by an ionization chamber placed in front of the target. The ionization chamber was calibrated using a ^{209}Bi monitor, according to the yield of the isomer ^{204m}Pb and the γ-lines at energies of 899.15 and 911.74 keV, as well as by using the emulsion technique, according to the number of prongs produced in the emulsion.

The times of irradiation, cooling (from the termination of irradiation to the beginning of measurement) and measurement varied depending on the half-life of the nuclei produced by the reaction.

The γ-ray spectrum measurements were performed using a Ge(Li) spectrometer with a resolution of 2.5 keV at E_γ=1332.5 keV of ^{60}Co. The accumulated γ-ray spectra were treated using standard codes on a BESM-6 computer.

The isotopic composition of the Sm_2O_3 target 23.264 g in weight is shown in Table 1. The monoisotope was provided to us by the State Foundation of Stable Isotopes.

Table 1

The isotopic composition of the Sm_2O_3 target

A	144	147	148	149	150	152	154
%	–	–	0.1%	0.1%	0.1%	99.0%	0.7
Admixtures of other isotopes	Eu 0.08%		Nd 0.05%		Pr 0.05%		

3. RESULTS OF MEASUREMENTS

In Table 2 are given the γ-ray energies (E_γ) of the isotopes produced in the reactions $Sm(\pi^-;yp,xn)$, the spins (I^π) and half-lives ($T_{1/2}$) of the isotopes in the ground and isomeric states. Parts of the γ-ray spectra due to the isotopes produced and fragments of the decay schemes of the isotopes ^{151}Nd, ^{151}Pm and ^{163}Tb are shown in Figs.1-3.

Table 2

The identification of the isotopes formed in the reaction $^{152}Sm(\pi^-;yp,xn)$ according to E_γ, $T_{1/2}$ and I^π

	(Z-1) $^{152}_{62}Sm(\pi^-,xn)^{152-x}_{61}Pm$			(Z-2) $Sm(\pi^-,pxn)^{152-1-x}_{60}Nd$			(Z-3) $Sm(\pi^-,2pxn)^{152-2-x}_{59}Pr$		
A	$T_{1/2}$	I^π	E_γ (keV)	$T_{1/2}$	I^π	E_γ (keV)	$T_{1/2}$	I^π	E_γ (keV)
151g	28h	$5/2^+$	177.13, 239.96, 275.18, 340.07, 340.07, 445.69	12.4min	$3/2^+$		4s		
m									
150g	2.7h	(1^-)	333.9, 831.8 1165.8,1324.5				10s	$(0^-,1^-,2^-)$	
m									
149g	53.1h	$7/2^+$	286.0	1.37h	$5/2^-$	1143,211.3 270.1, 423.5 540.6	28s	$5/2^+,7/2^+$	
m							2.3min		
148g	5.37d	1^-			0^+		1.98min		
m	41.3d		550.2,629.8						
147g	2.62y	$7/2^+$		10.98d	$5/2^-$	531.4	12.0min		
m									
146g	5.53y	$(2^-,3^-,4^-)$			0^+		24.0min	$(2,3^-)$	
m									
145g	17.7y	$5/2^+$			$7/2^-$		5.98h	$5/2^+,7/2^+$	
m									
144g	1.0y	$5^-,6^-$			0^+		17.3min	0^-	
m							7.2min		
143g	265d	$5/2^+$			$7/2^-$		13.57d	$7/2^+$	
m									
142g	40.5s	1^+			0^+		19.2h	2^-	
m							14.6min	$5/2^+$	
141g	20.9min	$5/2^+$	1223.6	2.5h	$3/2^+$	1126.7,1292.5		$5/2^+$	
m				62s	$11/2^-$				
140g	9.2s			3.38d	0^+		3.4min	1^+	
m	5.8min	(8^-)	419,774,1028						
139g	4.1min	$1/2,5/2^+$		29.7min	$3/2^+$		4.5h	$5/2^+$	
m	0.5s			5.5h	$11/2^-$	113.9,738.1			
138g	3.5min	(3^+)		5.1h	0^+		1.44min	1^+	
m							2.02h	$7^-,8^-$	3023,1038.2

3.1. The reaction $^{152}Sm(\pi^-,p)^{151}Nd$ ($I^\pi = 3/2^+$, $T_{1/2} = 12$ min)

The decay scheme of ^{151}Nd has been well studied /8/. Three intense γ-lines due to the decay of ^{151}Nd are known to lie at energies $E_\gamma = 116.8$ keV (22.2%), 255.7 keV (7.6%) and 1180.9 keV (10%) respectively (see Fig.1). In the spectrum, these lines could not be separated fairly well from the background level. This indicates the low probability of the reaction $^{152}Sm(\pi^-,p)$. The estimate of the upper limit of the one-proton emission probability is equal to $(3-4)\times10^{-4}$ per stopped π^-. Unfortunately there is no possibility of comparing it with the reaction (π^-,pn) because of the stability of the isotope ^{150}Sm (see Table 2).

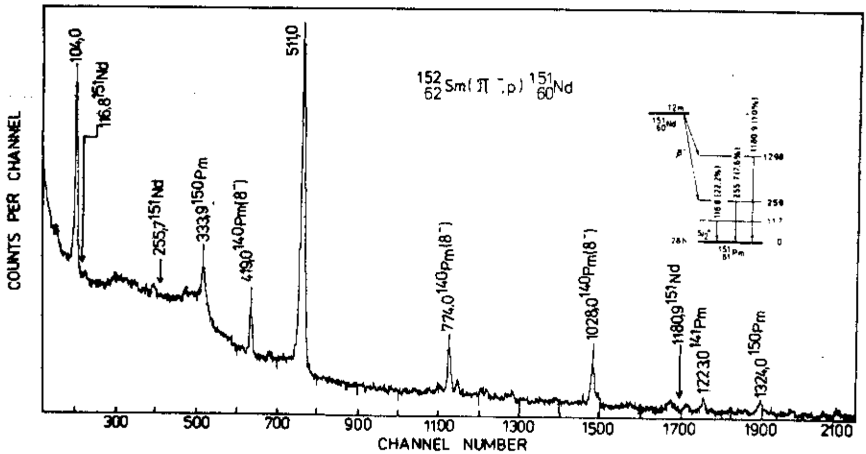
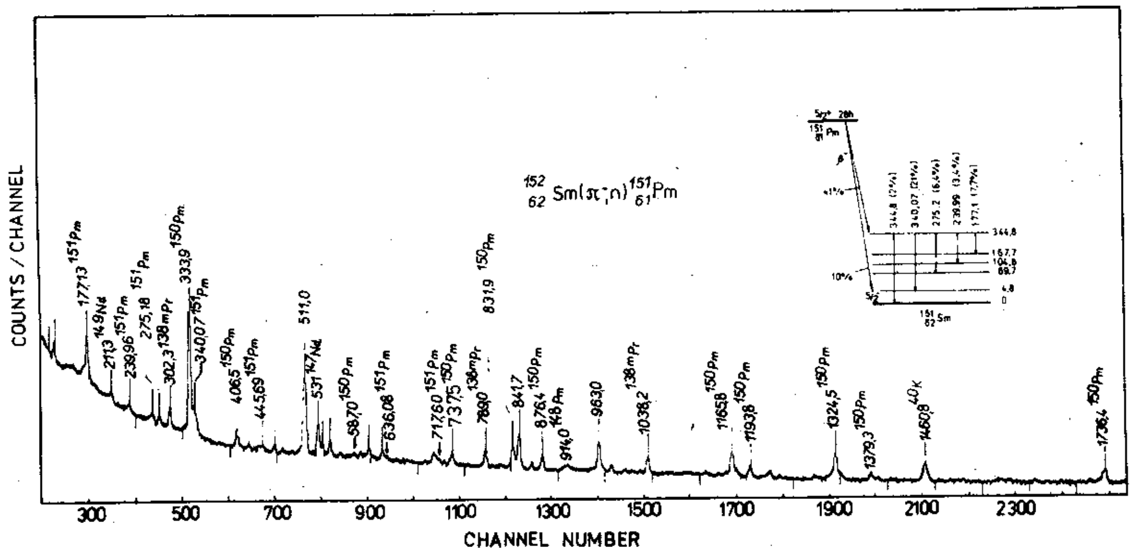


Fig.1. The γ-ray spectrum of the isotopes formed in the reaction ($^{152}Sm + \pi^-$) and a fragment of the decay scheme of the isotope ^{151}Nd.

3.2. The reaction $^{152}Sm(\pi^-,n)^{151}Pm$ ($I^\pi = 5/2^+$, $T_{1/2} = 28$ h)

In the γ-ray spectrum shown in Fig.2 one can clearly see the most intense lines corresponding to the decay of ^{151}Pm at 117.13 keV (7.7%), 239.95 keV (3.4%), 275.2 keV (6.4%) and 340.07 keV (21%). It whould be noted that the isotope ^{151}Pm can be formed not only via the channel of interest to us, which involves the emission of one neutron, but also as a result of the background reaction $^{154}Sm(\pi^-,3n)^{151}Pm$ from the 0.7% admixture of the isotope ^{154}Sm in the ^{152}Sm target. To estimate the yield of the isotope ^{151}Pm produced, only in the reaction (π^-,n) of interest to us, we have carried out a similar



<u>Fig.2.</u> The γ-ray spectrum of the isotopes formed in the reaction ($^{152}Sm+\pi^-$) and a fragment of the decay scheme of the isotope ^{151}Pm.

irradiation of a target made of natural samarium. From the yield of the isotope ^{151}Pm in the π^- capture reaction on the natural mixture at $W = 4.5 \times 10^{-1}$ and in the monoisotopic target at $W = 1.6 \times 10^{-2}$ the upper limit for the reaction (π^-,n) has been found to be equal to $(2.5 \pm 0.9) \times 10^{-3}$ per stopped π^-.

3.3. The reaction ^{164}Dy$(\pi^-,n)^{163}$Tb $(I^\pi = 3/2^+,\ T_{1/2} = 19.5$ min$)$

The most intense lines corresponding to the decay of ^{163}Tb (at 351.2 keV (26%), 389.8 keV (25.2%) and 421.9 keV (11.9)) are shown with arrows in the γ-ray spectrum presented in Fig.3. This reaction is free from background processes involving the formation of terbium since ^{164}Dy is the heaviest isotope. Thus we have obtained the probability of the reaction ^{164}Dy(π^-,n) to be equal to $(1.3 \pm 0.8) \cdot 10^{-3}$ per stopped π^-.

In principle, the formation of the final nuclei ^{151}Nd, ^{151}Pm and ^{163}Tb is possible as a result of the formation of neutrons and protons at pion capture followed by reactions of the type (N,2N) in the target substance. Such estimates were made using the technique described in ref.[9], on the basis of the data on the nucleon yield[10] and of data on the cross sections

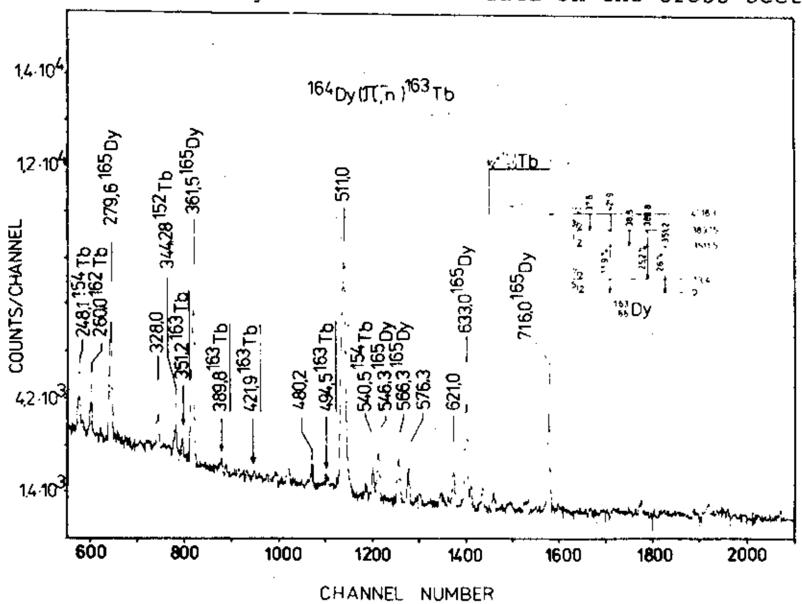


Fig.3. Part of the γ-ray spectrum of the isotopes formed in the reaction ^{164}Dy$(\pi^-;\gamma p,xn)$ and a fragment of the decay scheme of the isotope ^{163}Tb.

of the reactions (N,2N)[11,12]. The following estimates for the isotopic yields have been obtained, per stopped pion:

2.6×10^{-5} for the reaction $^{152}Sm(p,2p)^{151}Pm$,

3.8×10^{-8} for $^{152}Sm(n,2p)^{151}Nd$,

1.6×10^{-4} for $^{152}Sm(n,pn)^{151}Pm$ and

1.7×10^{-4} for $^{164}Dy(n,pn)^{163}Tb$.

One can see that these corrections can be neglected.

4. DISCUSSION OF RESULTS

All the presently known experimental data on the single-proton and single-neutron emission probabilities are listed in Table 3. From this Table it is seen that the value of the

Table 3

The probability of single-nucleon emission

	I_i	Reaction	I_f	Probability of reaction	Ref.
1.	-	^{6}Li, ^{7}Li, ^{12}C (π^-,n)	-	$(1-2)\times10^{-3}$	/3/
2.	0^+	$^{12}_{6}C(\pi^-,p)$ $^{11}_{5}Be$	$1/2^+$	$(4.5\pm0.8)\times10^{-4}$	/4/
3.	$7/2^-$	$^{45}_{21}Sc(\pi^-,p)$ $^{44}_{19}K$	2^-	$\leq 6.1\times10^{-4}$	/6/
4.	$2/2^-$	$^{45}_{21}Sc(\pi^-,p)$ $^{44}_{19}K$	2^-	$\sim 10^{-5}$	/12/
5.	$7/2^-$	$^{59}_{27}Co(\pi^-,p)$ $^{58}_{25}Mn$	3^+	$\leq 0.87\times10^{-4}$	/6/
6.	$1/2^-$	$^{89}_{39}Y(\pi^-,p)$ $^{88}_{37}Rb$	2^-	$\leq 6.9\times10^{-4}$	/6/
7.	$9/2^+$	$^{93}_{41}Nb(\pi^-,p)$ $^{92}_{39}Y$	2^-	$\sim 10^{-5}$	/12/
8.	$7/2^+$	$^{133}_{55}Cs(\pi^-,p)$ $^{132}_{53}I$	4^+	$\sim 1.3\times10^{-4}$	/6/
9.	$7/2^+$	$^{133}_{55}Cs(\pi^-,p)$ $^{132}_{53}I$	4^+	$(2.0\pm0.8)\times10^{-5}$	/12/
10.	$5/2^+$	$^{141}_{59}Pr(\pi^-,p)$ $^{140}_{57}La$	3^-	$\leq 3\times10^{-4}$	/6/
11.	0^+	$^{152}_{62}Sm(\pi^-,p)$ $^{151}_{60}Nd$	$3/2^+$	$(3-4)\times10^{-4}$	present paper
12.	0^+	$^{152}_{62}Sm(\pi^-,n)$ $^{151}_{61}Pm$	$5/2^+$	$(2.5\pm0.9)\times10^{-3}$	present paper
13.	0^+	$^{164}_{66}Dy(\pi^-,n)$ $^{163}_{65}Tb$	$3/2^+$	$(1.3\pm0.8)\times10^{-3}$	present paper
14.	$7/2^+$	$^{181}_{73}Ta(\pi^-,n)$ $^{180m}_{72}Hf$	8^-	$\sim 10^{-5}$	/5/
15.	$3/2^+$	$^{197}_{79}Au(\pi^-,p)$ $^{196m}_{77}Ir$	$(10,11^-)$	$\leq 3.3\times10^{-5}$	/6/

probability for one-proton emission in the reaction $^{152}Sm(\pi^-,p)$ obtained in the present paper to be at a level of 3.6×10^{-4} agrees well with all the previously obtained data except for those of ref.[13].

The probability of one-neutron emission in the reactions $^{152}Sm(\pi^-,n)$ and $^{164}Dy(\pi^-,n)$, which have been set at $(2.5\pm0.9)\times10^{-3}$ and $(1.3\pm0.8)\times10^{-3}$ agree well with the data of ref.[3], but are at variance with the results of refs.[5,13].

The substantial difference between the probabilities of π^--absorption followed by neutron and proton emission, observed in the given experiment, suggests that at least for the reactions involving the emission of single nucleons pion absorption mechanisms other than the two-nucleon particle one play a significant part. In fact, in the presence of only two-particle mechanism, the diagrams of reactions involving neutron and proton emission are similar (see Fig.4) and the neutron and proton yields should be of the same order of magnitude.

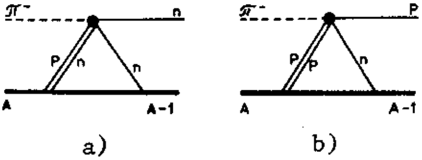


Fig.4. Diagrams of π^--capture reactions followed by single-proton and single-neutron emission.

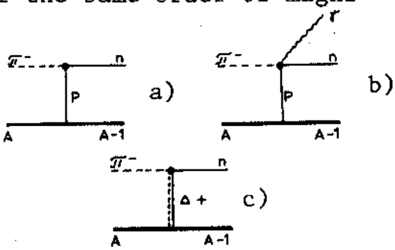


Fig.5. Diagrams of π^- capture reactions followed by single-neutron emission.

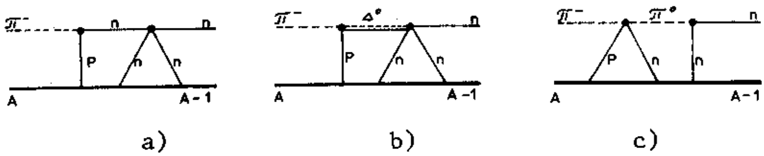
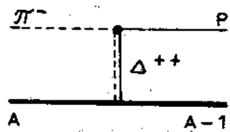


Fig.6. Diagrams of π^- capture reactions followed by single-neutron emission.

Then one can assume that for the reaction involving the emission of a single neutron the polar diagrams shown in Fig.5 are the main contributors. In this case both the pick-up reactions accompanied by the formation of the residual nucleus

Fig.7. Diagrams of a π^- capture reaction on the Δ^{++} isobar, followed by single-proton emission.



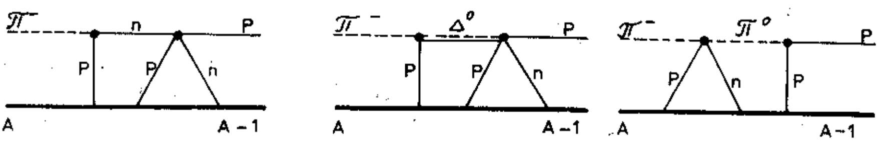
in one of the states that are stable against nucleon emission, and the reaction involving the simultaneous γ-ray emission are possible. The simultaneous emission of π^0 and neutron in the case of ^{152}Sm and ^{164}Dy is forbidden because of the high neutron binding energy. The contribution from various multiple processes, the simplest of which are given in Fig.6, evidently leads to corrections of the highest order of smallness.

The only kind of the polar diagram for the reaction involving the emission of one proton is the π^-- absorption on the admixture of isobaric configuration in the nucleus (Fig.7). The sequential calculations of the role of such a mechanism are practically impossible; on the contrary, the reaction (π^-,p) is more likely to be used to estimate the probability of the existence of the Δ^{++}-isobar in the nucleus /6,7/.

Other possible mechanisms of the reaction involving the emission of a proton are multiple processes similar to those indicated earlier for the reaction accompanied by neutron emission (cf. Figs.6 and 8, and also Fig.4).

Apparently the most substantial process of these are neutron charge exchange on nuclear protons (Fig.8a) and a rather similar process of the capture on a nucleon pair followed by neutron capture (Fig.4b), and also the charge exchange of π^- into π^0 on nuclear protons, followed by the capture of π^0 (Fig.8c).

One can hardly expect that precise calculations of the diagrams can be performed in the case where a considerable number of final states of the residual nucleus are present. Therefore it is of interest to estimate the yield of single protons from the mentioned multi-stage reaction mechanism compared with single neutron emission.



a) b) c)

Fig.8. Diagrams of π^- capture reactions followed by single-proton emission.

Let us consider π^- absorption on a pp-pair. Assuming the π^--absorption on a nucleon pair to be the main process, for ^{152}Sm we obtain the probability of absorption on a pp-pair to be about 0.25. Of the proton and neutron produced with a kinetic energy of 70 MeV, one of the nucleons can in principle be captured in the nucleus, and the other can escape leading to a contribution to one-nucleon emission. The neutron capture probability is determined by the value of the (n,γ) reaction cross section. It is known that the cross section of the reaction (n,γ) on heavy nuclei decreases sharply with energy. At $E_n \approx 0.35$ MeV it is equal to about 10^{-2} of the total cross section value for natural samarium /14/. To evaluate the role of the two-nucleon capture of the pion in the course of proton emission, data on the radiative capture of neutrons at energies of several tens of MeV are necessary. For ^{152}Sm, such data are not available. If we make use of the values of total cross section and the (n,γ) reaction cross section for ^{158}Gd at neutron energy of 20 MeV (ref. /15/), we obtain the probability of neutron capture equal to 0.8×10^{-3}, and this gives for the yield of the reaction (π^-,p) a value of 2×10^{-4}.

The contribution of the neutron charge transfer to be a proton (Fig.8a) was calculated using a quasiclassical method similar to that employed in ref. /16/ to estimate nuclear effects in pion production. The case of the scattering of ~140 MeV neutrons on protons was considered, in which the neutron scattered has an energy below 20 keV and the probability of its capture by the nucleus is still sufficiently high. According to ref. /14/, the cross section of the reaction (n,γ) on samarium at an energy of 20 keV is about 0.1 of the total cross section. Under this condition, the recoil proton is emitted forward in a narrow angle, about 0.7°, with an energy practically equal to that of the incident neutron. By using the np - scattering data /17/ we obtain a cross section of such a process to be 0.2 mb. Hence, the passage by neutrons, in the nucleus, of a distance equal, on the average, to the nuclear radius leads to the formation of about 10^{-2} single protons per neutron. Taking the Pauli principle into account can only reduce this estimate /17/.

The role of the process involving the formation of an isobar in the intermediate state (Fig.8b) can apparently be neglected for the capture of stopped pions because of a large energy shift in the initial and intermediate channels.

The π^- charge exchange effect on nuclear protons, followed by π^0 capture (Fig.8c) can be estimated by extrapolating the

$\pi^- + p \to \pi^\circ + n$ reaction cross section data to the zero pion energy, and this gives a value of about 5 mb. Taking into account data on pion absorption in heavy nuclei at a distance of about 0.8 fm from the nuclear surface[18], we obtain a value of 3×10^{-2} π° per stopped π^-. However, as it is required that the neutron formed with an energy of about 4 MeV be absorbed in the nucleus, the contribution from the pion charge exchange process should be decreased in the ratio $\sigma_{n\gamma}/\sigma_t \sim$ $\sim 2 \times 10^{-3}$ at these neutron energies[19]. The subsequent stage of π° absorption involving the emission of a proton can be considered to be similar to the π^--absorption, according to the polar diagram (Fig.5a). Therefore, the obtained estimate of about $\sim 10^{-4}$ constitutes the number of protons emitted in the process under consideration per neutron emitted.

Thus the estimates cited here show that the ratio of the yields of single protons and neutrons at the capture of stopped pions at rest on samarium nuclei should be below 10^{-2} (if only the considered nuclear effects are taken into account and less than 0.1 taking into account the two-nucleon mechanism of pion absorption. On the other hand, the experimental upper limit of the ratio $\sigma(\pi^-,p)/\sigma(\pi^-,n)$ obtained in the present paper is equal to 0.14. The experimental limit of the ratios of $\sigma(\pi^-,p)$ from ref.[4] to $\sigma(\pi^-,n)$ from ref.[3] is equal to 0.23. We note that the value of the corresponding ratio, calculated taking into account the possible π condensation in the nucleus is equal to 0.06 and does not depend on the amplitude of the condensate field[20]. Hence it follows that the further, more accurate measurements of the yield of the reaction (π^-,n) and the determination of the ratio of the yields of single protons and neutrons are very important.

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