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Поглощение покоящихся π^--мезонов деформированными ядрами

Приведены экспериментальные результаты исследования механизма поглощения покоящихся π^--мезонов деформированными ядрами Ta, Lu, Tm, Er и Ho. С помощью активационной методики определен выход изотопов гольмия в реакции $^{169}Tm(\pi^-; 1p, xn)$. Для ряда изотопов рассчитаны изомерные отношения. Для двух ядер ^{159}Er и ^{159}Ho определено изобарное отношение $I = (9,8 \pm 2,9)$. Установлена связь между экспериментальной величиной изобарного отношения и отношением количества np- и pp-пар на поверхности ядра. Поглощение π^--мезона для ядра ^{169}Tm характеризуется отношением $R = N_{np}/N_{pp} = (4,4 \pm 1,4)$. Результаты показывают, что возбуждение вращательного движения ядра мало зависит от массы, заряда и деформации исходного ядра, а является универсальным фактом, связанным с механизмом поглощения пиона на нуклонных ассоциациях - кластерах.

Работа выполнена в Лаборатории Вычислительной техники и автоматизации.

Препринт Объединенного института ядерных исследований. Дубна 1978

Abazov V.M., Butsev V.S., Butseva G.L. **E15 - 11713**

Negative Pion Capture at Rest by Deformed Nuclei

The experimental results of investigation of the mechanism of negative pion capture at rest by deformed Ta, Lu, Tm, Er and Ho nuclei are presented. The Ho isotope yield has been determined by the activation method. The isomeric ratios have been calculated for a number of isotopes. The isobaric ratio for ^{159}Er and ^{159}Ho has been found to be $I = (9.8 \pm 2.9)$. The relation between the experimental value of the isobaric ratio and that of the amount of np- and pp-pairs on the nuclear surface has been established to be $R = N_{np}/N_{pp}$ $I-1/2 = (4.4 \pm 1.4)$. The results show that the excitation of the rotational nuclear motion is weakly dependent on the mass, charge and deformation of the initial nucleus, and it is a universal fact related to pion absorption on nucleon associations or clusters.

The investigation has been performed at the Laboratory of Computing Technique and Automation.

Preprint of the Joint Institute for Nuclear Research. Dubna 1978

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1. INTRODUCTION

The experiments performed in recent years on highly intensive negative pion beams have shown that in negative pion capture by the atomic nucleus the production of neutron-deficient isotopes /1-7/ occurs and the intensive excitation of rotational states with spins up to 37/2 h is observed in residual nuclei.

The observed effect of nuclear rotational motion is a strong argument for the cluster mechanism of negative pion absorption at rest. At present there are comparatively few experimentally established facts indicating to the cluster mechanism of pion absorption. Therefore, a further study of the excitation of nuclear rotational motion in pion capture can give additional information about this mechanism.

It was of interest also to expand the region of nuclei where negative pion capture has been studied. For example, to pass over from the spherical nuclei to the deformed ones, it was interesting to clear out whether the deformation of the initial nucleus affects the excitation mechanism of high spin states.

For this purpose the capture of negative pions by deformed Ta, Lu, Tm, Er and Ho has been studied. The preliminary results of these investigations have been reported in refs. /8,9/.

2. EXPERIMENT

The experiment has been performed using the negative pion beam fron the JINR synchrocyclotron. Pions of $E = 30$ *MeV* were moderated in 2 g/cm^2 targets. The density of pion stops in target was $10^5 g^{-1} sec^{-1}$.

The gamma-ray spectra of beta-active nuclei produced in negative pion capture were investigated using the spectrometers with Ge(Li) detectors having a 2.5 *keV* resolution for $E_\gamma = 1332$ *keV*. The method applied for investigations has been described in more detail earlier [4]. Typical spectra of gamma-rays are shown in *Figs. 1-5*.

During the experiment the succession of experimental measurements of gamma-spectra were recorded by the HP-2116C computer. There was a possibility to output data for express processing and to correct parameter measurements. All the information stored in the computer memory was tape-recorded for further processing.

The gamma-spectra were processed by the programme modules "SIMPEC" [10] within the system of spectra processing (SOS) [11].

The produced isotopes were identified by gamma-ray energies and their intensity relation. The isotope half-life was determined by the activity reduction of the most intensive gamma-lines. The results of identification are presented in *Tables 1-5*.

2.1. A Target (Z = 73)

Earlier we have reported [12] that gamma-lines of the high spin ^{177m_2}Hf isotopes ($T_{1/2} = 51.4$ *min*, $I^\pi = 37/2$) were identified in the gamma-ray spectrum of Hf isotopes produced in pion absorption by Ta nuclei. The fact itself of such a high spin-isomer was so wonderful that all our attention was focused on the understanding of this phenomenon.

In repeated exposures by target pions ^{170}Hf, ^{171}Hf, ^{173}Hf gamma-lines have been observed (see *Table 1*) along with the known gamma-lines of the ^{177m_2}Hf isomer.

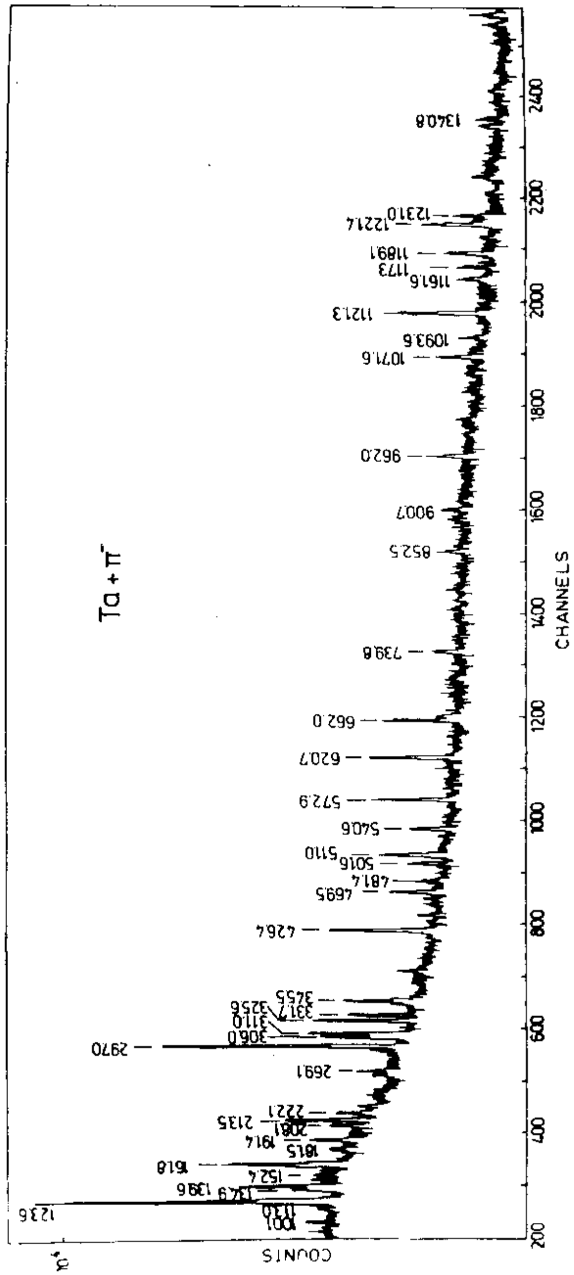

Fig. 1. Gamma-ray spectrum of the Hf *isotopes produced in the* ^{181}Ta(π^-, xn) *reaction.*

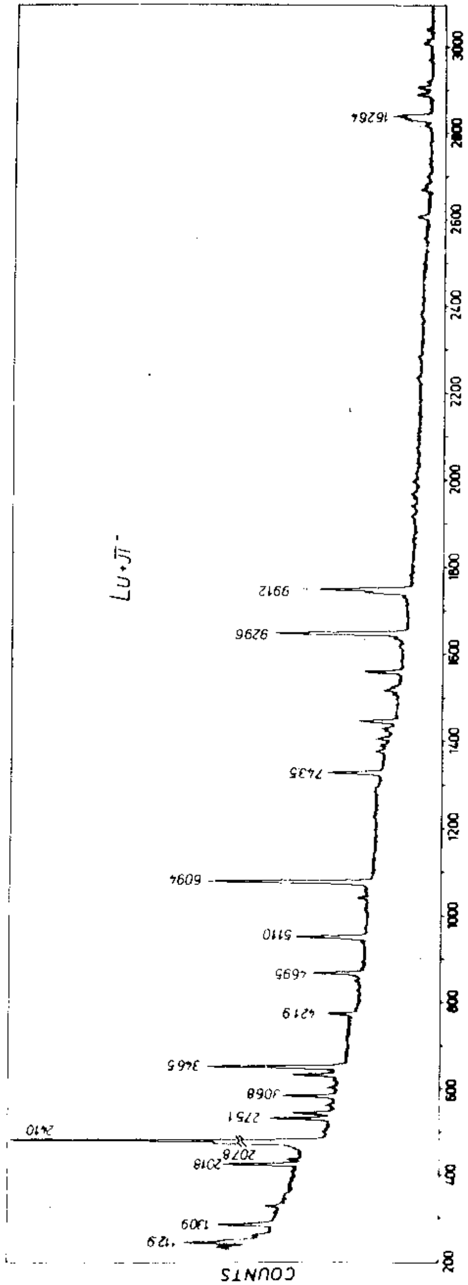

Fig. 2. Gamma-ray spectrum of Yb, Tm *and* Er *isotopes produced as a result of a* Lu *target activation by negative pions.*

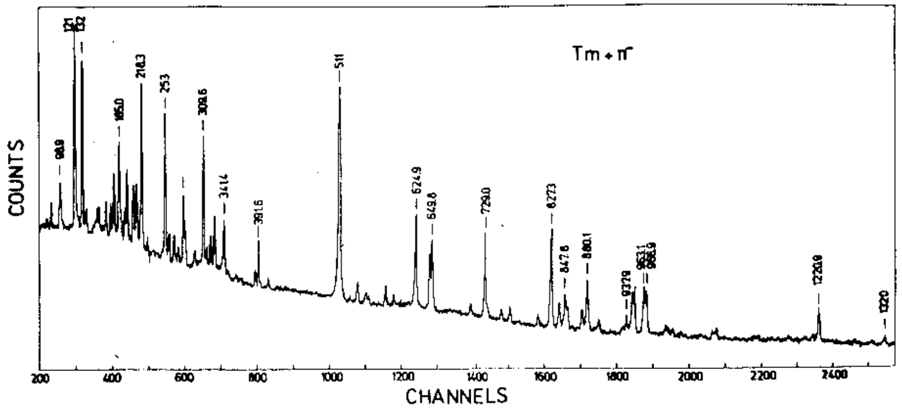

Fig. 3. Gamma-ray spectrum of Er *and* Ho *isotopes produced in the* ^{169}Tm(π^-;yp,xn)*reactions.*

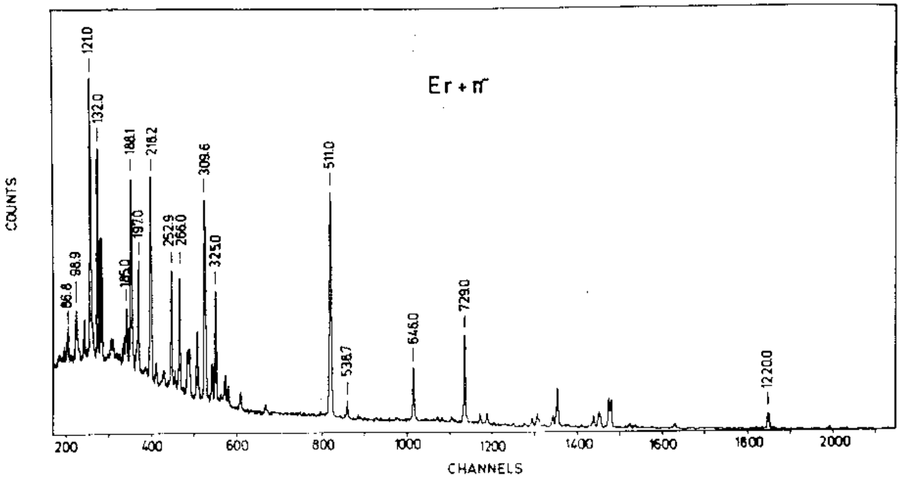

Fig. 4. Gamma-ray spectrum of Ho, Dy *and* Tb *isotopes produced in an* Er *target irradiation with pions.*

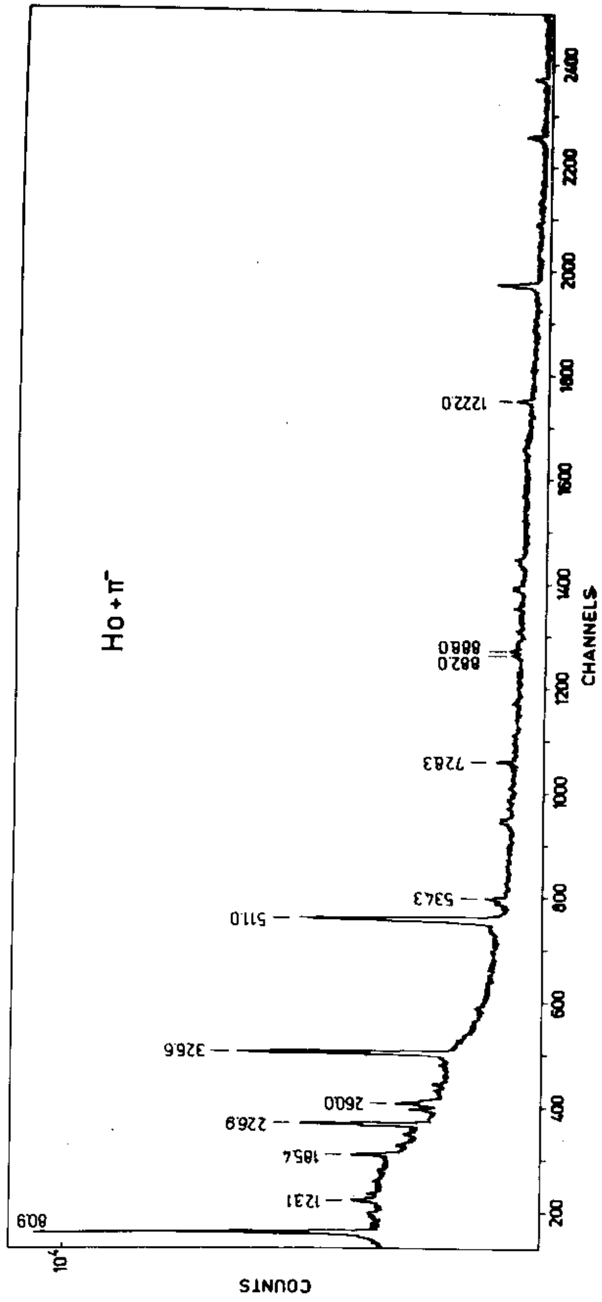

Fig. 5. Gamma-ray spectrum of Dy , Tb *and* Gd *isotopes produced in the* Ho(π^-, γp, xn) *reaction.*

Table 1

Isotopes (isomers) produced in the Ta + π^- reaction

A	$(99{,}988\,\%)\ ^{181}_{73}\mathrm{Ta}(\pi^-, xn)_{72}\mathrm{Hf}$			A	$^{181}_{73}\mathrm{Ta}(\pi^-, pxn)_{71}\mathrm{Lu}$		
(Z-1)	$T_{1/2}$	J^π	$E_{\gamma\,(\mathrm{KeV})}$	(Z-1)	$T_{1/2}$	J^π	$E_{\gamma\,(\mathrm{KeV})}$
180 g	∞	0^+					
m	5,5 h	6^-					
179 g	∞	$9/2^+$		179 g	4,6 h	$(7/2^+)$	
m	18,7 s	$11/2^-$		m			
178 g	∞	0^+		178 g	28,4 min	(0^+)	
m	4,3 s	(8^-)		m	22,7 min	(0, 4)	
177 g	∞	$7/2^-$		177 g	16,7 d	$(7/2^+)$	
m_1	1,1 s	$23/2^+$		m	161 d	$23/2^-$	
m_2	51,4 min	$37/2^-$	214,0 ; 277,3 ; 311,5 326,7				
176 g	∞	0^+		176 g	3·10[illegible] y	7^-	
m	—			m	3,68 h	1^-	
175 g	70 d	$5/2^-$		175 g	∞	$7/2^+$	
m				m			
174 g	∞	0^+		174 g	3,3 y	1^-	
m				m	142 d	6^-	
173 g	23,6 h	$1/2^-$	123.6 134.9 139.6 2970 3060 311.0 8980	173 g	1,37 y	–	
m				m			
172 g	1,87 y	0^+		172 g	6,7 d	4^-	181,5, 810,0, 912,1 1093,6
m							
				m	3,7 min	(1^-)	
171 g	12,2 h		1221 2691 3475 469.5 6620 666.0 788.3 852.5 1071.4 1161.6	171 g	8,22 d	$(7/2^+; 9/2^-)$	739,8
m				m	76 s		
170 g	16,0 h	0^+	120.2 164.8 2081 481.4 501.6 5406 5729 620.7	170 g	2,0 d	0^+	
m				m	0,70 s	4^-	
169 g	3,25 min			169 g	1,42 d	$7/2^+$	191,4; 379,2, 891,0 962,0; 1173,0, 1273,0
m							
				m	2,7 min	$1/2^-$	
168 g	26 min	0^+		168 g	5,5 min	(1^-)	
m				m	6,7 min		
167 g	2,05 min			167 g	55 min		
m				m			
				166 g	3,3 min		
				m			
				165 g	11,8 min		
				m			

It should be noted that the chosen time factors (irradiation, cooling and measuring times of the target) did not allow us to identify the isotopes which had their half-lives either shorter than 50 seconds or longer than 50 days.

Table 2

Isotopes (isomers) produced in the Lu + π^- reaction

A (Z - 1)	$^{176(2.6\%)}_{175(97.4\%)}{}_{71}Lu(\pi^-,xn)_{70}Yb$			A (Z - 2)	$_{71}Lu(\pi^-,pxn)_{69}Tm$			A (Z - 3)	$_{71}Lu(\pi^-,2pxn)_{68}Er$		
	$T_{1/2}$	J^{π}	E_{γ} (KeV)		$T_{1/2}$	J^{π}	E_{γ} (KeV)		$T_{1/2}$	J^{π}	E_{γ} (KeV)
174 g	∞	0^+		174 g	54min						
m				m							
173 g	∞	$5/2^-$		173 g	8.2 h		399.0 461.8	173 g	14min		
m				m				m			
172 g	∞	0^+		172 g	63.6 h	2^-	1093.8 1529.7 1608.4	172 g	49h	0^+	
m				m				m			
171 g	∞	$1/2^-$		171 g	1.92 y	$1/2^+$		171 g	7.5 h	$5/2^-$	111.6 124.0 295.9 308.2
m				m				m			
170 g	∞	0^+		170 g	129d	1^-		170 g	—	0^+	
m				m				m			
169 g	30.7 d	$1/2^+$		169 g	∞	$1/2^-$		169 g	9.3 d	$1/2^-$	
m	46 s			m				m			
168 g	∞	0^+		168 g	93 d			168 g	∞	0^+	
m				m				m			
167 g	17.7 min	$5/2^-$	106.0 113.3 176.1	167 g	9.25 d		207.9	167 g	∞	$7/2^+$	
m				m				m			
166 g	56.7 h	0^+		166 g	7.7 h		184.4 779.8 1275.3	166 g	∞	0^+	
m				m				m			
165 g	10.5 min			165 g	30.1 h		242.8 295.9	165 g	10.3 h	$5/2^-$	
m				m				m			
164 g	75.8 min	0^+	445.0 675.0	164 g	20min	1^+	208.1	164 g	∞	0^+	
m				m	51min			m			
163 g	11.1 min		123.2 130.9 161.5 860.3	163 g	1.8 h	$1/2^+$	104.3 239.5 1397.5 1434.2	163 g	75min	$5/2^-$	
m				m				m			
162 g	18.9 min		118.8 163.5	162 g	21.8min		798.5 900.3	162 g	∞	0^+	
m				m				m			
161 g	41 min			161 g	37min			161 g	3.1 h	$3/2^-$	
m				m				m			
160 g	48min			160 g	9.2 min			160 g	28.6 h	0^+	
m				m				m			
159 g	4.6 min			159 g	12 min		220.2 289.6 348.3	159 g	36min		
m				m				m			

2.2. A Lu Target (Z = 71)

Table 2 presents the results of identifying the gamma-rays of Yb, Tm and Er isotopes produced in irradiating a Lu target by negative pions.

On the face of it one may assume that Tm isotopes with (Z – 2) can be produced with a greater probability than Yb isotopes with (Z–1).

This may be related to the fact that a greater number of Yb isotopes are stable. Thus, a favourable situation appears for observing rather weak gamma-lines of Tm isotopes in the gamma-ray spectrum. The observed spectrum of isotope masses is rather wide. It corresponds to the emission of 2-16 nucleons from the nucleus.

The gamma-lines of the ^{171}Er isotope with (Z–3) have been identified in the gamma-ray spectrum. It could be produced in the ^{175}Lu(π^-, 2p, xn) reaction.

2.3. A Tm Target (Z = 69)

Table 3 presents the results of gamma-ray identification of Er and Ho isotopes produced in the ^{169}Tm(π^-, xn) and ^{169}Tm(π^-,pxn) reactions, respectively.

As is seen from *Table 3*, the high spin nuclear states can arise effectively when one proton is emitted from the nucleus along with neutrons.

Thus, as a result of pion absorption by Tm nuclei a wide mass spectrum of Ho isotopes (A = 155-167) corresponding to the emission of one proton and 2-13 neutrons from the Tm nucleus, is observed. High spin ^{158m_2}Ho(9^+) and ^{160m}Ho(9^+) isomers have been identified among them, which have been recently observed by H.Schepers /13/ and V.G.Kalinnikov /14/, independently.

Fig. 6 shows the relative yields of Ho isotopes in the ^{169}Tm(π^-, pxn) reaction. Ho isotope yields were defined by the intensities of gamma-rays by taking into account their detection efficiency and the coefficients of gamma-ray self-absorption in targets.

Table 3

Isotopes (isomers) produced in the Ta + π^- reaction

A	${}^{169}_{69}$Tm $(\pi^-, xn)_{69}$Er			A	${}^{169}_{69}$Tm $(\pi^-, pxn)_{67}$Ho		
(Z-1)	$T_{1/2}$	J^π	E_γ(keV)	(Z-2)	$T_{1/2}$	J^π	E_γ(keV)
168 g	∞	0^+		168 g	3 min		
m	–			m			
167 g		$7/2^+$		167 g	3.1 h	$7/2^-$	207.8 321.3 346.5
m	2.3 s			m			
166 g	∞	0^+		166 g	26.7 h	0^-	
m	—			m	$1.2\cdot10^3$ y	(7^-)	
165 g	10.3 h	$5/2^-$		165 g	∞	$7/2^-$	
m	—			m			
164 g		0^+		164 g	29 min		73.4 91.5
m				m	37.5 min		
163 g	75 min	$5/2^-$		163 g	33 y	$7/2^-$	
m	– –			m	1.1 s	$1/2^+$	
162 g	∞	0^+		162 g	15 min	1^+	80.7 1319.6
m				m	68 min	6^-	185.0 282.9 937.9 1220.0
161 g	3.1 h	$3/2^-$	211.15 826.5	161 g	2.5 h	$7/2^-$	77.5 103.8
m				m	6.7 s	$1/2^+$	
160 g	28.6 h	0^+		160 g	26 min	5^+	645.4 729.0
m				m_1	5.0 h	2^-	392.5
				m_2	~10 h	9^+	879.4 962.3 966.2
159 g	36 min	$3/2^-$	205.9 624.4 649.6	159 g	33 min	$7/2^-$	56.7 79.9 100.6 121.0 132.0 152.4 155.8 173.1 177.6 186.3 217.7 252.9 258.9 309.6 838.7
				m	8.3 s	$1/2^+$	
158 g	2.3 h	0^+	93.1 195.6 248.6 296.0 358.3 386.9	158 g	11 min	5^+	847.0 948.8 994.4
m				m_1	29 min	2^-	425.4
				m_2	19.5 min	9^+	406.5 1484.6
157 g	25 min	$3/2^-$	121.9 391.4	157 g	12.6 min	$7/2^-$	86.5 193.4 280.0 297.0 341.1
m				m			
156 g	19.5 min	0^+		156 g	55 min	5^+	138.0 266.4 366.7
m				m	~1 h	2^-	136.0 266.0
155 g	5.3 min			155 g	48 min		240.3
m				m			
154 g	5.8 min			154 g	11.8 min		
m				m	3.3 min		
				153 g	9.3 min		
				m	2.0 min		
				152 g	2.4 min		
				m	52.3 s		

For a number of ^{158}Ho, ^{160}Ho and ^{162}Ho isotopes we could determine the isomer ratio $\xi = \sigma_m / \sigma_g$ (see *Table 6*). This value characterizes how effectively an isomer is produced. For example, by comparing the intensities of gamma-406 isomer of ^{158m_2}Ho(9^+) and the well-studied transition of ^{158m_1}Ho(2^-) and ^{158g}Ho(5^+) we have found the following isomer ratios: $\sigma_{m_2}/\sigma_{m_1} = (5.26 \pm 0.89)$, $\sigma_{m_2}/\sigma_g = = (1.15 \pm 0.25)$ and $\sigma_{m_1}/\sigma_g = (0.33 \pm 0.07)$.

The ^{160m_2}Ho(9^+) isomer was identified by 879.4, 962,3 and 966.2 *keV* gamma-lines . Its half-life determined by the reduction of these gamma-line activities is $T_{1/2} \simeq 50$ *min.* When comparing the intensities of gamma-transition from the decay of the ^{160m}Ho(9^+) isomeric state and the 645.4 *keV* gamma- transition from the decay of the ^{160g}Ho(5) ground state we have determined the isomeric ratio to be $\sigma_{m_2}/\sigma_g = (1.39 \pm 0.29)$.

In the gamma-ray spectrum of produced isotopes we have determined safely the 80.7 and 1319.6 *KeV* gamma-lines from the decay of the ground state of ^{162}Ho (1^+) and the 185.0, 282.9, 937.9 and 1220.0 *KeV* gamma-lines of the ^{162m}Ho(6^-) isomeric state. The isomeric ratio for this isotope is $\sigma_m/\sigma_g = (3.6 \pm 0.6)$.

2.4. An Er *Target* ($Z = 68$)

A wide mass range of Ho isotopes ($A = 155$-169) is also produced in pion capture by an Er target (*Table 4*).

No Dy isotopes in the Er(π^-, xn) reaction have been observed. This seems to be due to the fact that the majority of Dy isotopes of this range are stable.

Some isotopes of ^{152}Tb, ^{162}Tb and ^{164}Tb were identified in the Er$(\pi^-, 2pxn)$ reaction. This fact shows that the rotational nuclear motion arises not only in nuclei with (Z−1) and (Z−2) but in nuclei with Z three units smaller than that of target nuclei.

Table 4

Isotopes (isomers) produced in the Er + π^- reaction

A (Z-1)	170(15%):167(23%):166(33%) 168(27%) $_{68}$Er(π^-,xn)$_{67}$Ho $T_{1/2}$	J^π	E_γ(keV)
169 g	4.8 min	$1/2^+$	768.0 778.4 788.4 866.4
m			
168 g	3 min		
m			
167 g	3.1 h	$7/2^-$	207.8 321.3 346.5
m			
166 g	26.7 h	0^-	
m	$1.2\cdot10^3$ y	(7^-)	
165 g	∞	$7/2^-$	
m			
164 g	29 min		73.4 91.5
m	37 min		
163 g	$>10^3$ y	$7/2^-$	
m	1.1 s	$1/2^+$	
162 g	15 min	1^+	80.7 1319.6
m	68 min	(6^-)	185.0 282.9 937.2 1220.0
161 g	2.5 h	$7/2^-$	77.5 103.8
m	6.7 s	$1/2^+$	
160 g	26 min	5^+	645.4 729.0
m_1	5.0 h	2^-	392.5
m_2	~10 h	9^+	879.4 962.3 966.2
159 g	33 min	$7/2^-$	121.0 132.0 252.9 309.6
158 g	11 min	5^+	847.0 948.8 994.4
m_1	29 min	2^-	425.4
m_2	19.5 min	9^+	406.5 1484.6
157 g	12.6 min	$7/2^-$	297.0 341.1
m			
156 g	55 min	5^+	138.0 266.4 366.7
m	~1 h	2^-	
155 g	48 min		240.3
m			
154 g	11.8 min		
m	33 min		
153 g	9.3 min		
m	2.0 min		
152 g	2.4 min		
m	52.3 s		

A (Z-1)	$_{68}$Er(π^-,pxn)$_{66}$Dy $T_{1/2}$	J^π	E_γ(keV)
167 g	4.5 min		
m			
166 g	81.5 h	0^+	
m			
165 g	2.35 h	$7/2^+$	
m	1.3 min		
164 g	∞	0^+	
m			
163 g	∞	$5/2^-$	
m			
162 g	∞	0^+	
m			
161 g	∞	$5/2^+$	
m			
160 g	∞	0^+	
m			
159 g	144.4 d	$3/2^-$	
m			
158 g	∞	0^+	
m			
157 g	8.1 h	$(3/2^-)$	326.4
m			
156 g	∞	0^+	
m			
155 g	9.59 h	$(3/2^-)$	226.95
m			
154 g	10^6 y		
m			
153 g	6.29 h		
m			

A (Z-1)	$_{68}$Er(π^-,2pxn)$_{65}$Tb $T_{1/2}$	J^π	E_γ(keV)
164 g	3 min		168.9 215.1 610.9 688.5 754.8
m			
163 g	19.5 min		
m			
162 g	7.6 min		260.0 807.6
m			
161 g	6.9 d	$3/2^+$	
m			
160 g	72.1 d	3^-	
m			
159 g	∞	$3/2^+$	
m			
158 g	150 y	(3^-)	
m	10.5 s		
157 g	150 y	$(3/2^+)$	
m			
156 g	5.3 d	(3^-)	
m_1	5.4 h		
m_2	24.4 h		
155 g	5.32 d	$(3/2^+)$	
m			
154 g	21.4 h		
m_1	9.0 h		
m_2	22.6 h		
153 g	2.34 d	$(5/2^-)$	
m			
152 g	17.5 h		344.3 586.3
m	4.2 min		

2.5. A Ho Target (Z = 67)

As we have mentioned, the majority of Dy isotopes in the mass region under study are stable. Therefore no isotope yield in the ^{165}Ho(π^-, xn) reaction has been calculated.

The most favourable situation is here for analyzing the Tb isotope yield in the ^{165}Ho (π^-; pxn) reaction (*Table 5*).

Table 5

Isotopes (isomers) produced in the Ho + π^- reaction

A (Z-1)	$^{165}_{67}$Ho(π^-;xn)$_{66}$Dy $T_{1/2}$	J^π	E_γ(keV)
164 g	∞	0^+	
m			
163 g	∞	$5/2^-$	
m			
162 g	∞	0^+	
m			
161 g	∞	$5/2^+$	
m			
160 g	∞	0^+	
m			
159 g	144.4 d	$3/2^-$	
m			
158 g	∞	0^+	
m			
157 g	8.1 h	$3/2^-$	326.4
m			
156 g	∞	0^+	
m			
155 g	9.59 h	$3/2^-$	184.5 226.9
m			
154 g	∞		
m			
153 g	6.29 h		
m			
152 g	2.4 h	0^+	
m			
151 g	17 min		
m			
150 g	7.2 min	0^+	
m			
149 g	4.1 min		
m			
148 g	3.1 min		
m			

A (Z-2)	$^{165}_{67}$Ho(π^-;pxn)$_{65}$Tb $T_{1/2}$	J^π	E_γ(keV)
164 g	3.0 min		
m			
163 g	19.5 min		351.2 389.8 494.5
m			
162 g	7.6 min		80.9 185.4 260.1 807.6 882.4 888.2
m			
161 g	6.9 d	$3/2^+$	
m			
160 g	72.1 d	3^-	86.7 298.6 879.4 962.3 966.2
m			
159 g	∞	$3/2^+$	
m			
158 g	150 y	3^-	
m	10.5 s	0^-	
157 g	150 y	$3/2^+$	
m			
156 g	5.35 d	3^-	
m_1	24.4 h	4^+	88.9 199.2 356.5 534.3 1221.4 1384.4
m_2	5.0 h	0^+	
155 g	5.32 d	$3/2^+$	
m			
154 g	21.4 h	0^-	
m_1	9.0 h	3^-	123.1 247.9 892.9
m_2	22.6 h	(6^-)	
153 g	2.34 d	$5/2^-$	
m			
152 g	17.5 h		
m	4.2 min		283.5
151 g	17.6 h		
m			
150 g	3.5 h		
m	5.8 min	9^+	
149 g	4.1 h		
m	4.2 min		
148 g	70 min		
m	2.2 min		
147 g	1.61 h		
m	1.83 min		

A (Z-3)	$^{165}_{67}$Ho(π^-;2pxn)$_{64}$Gd $T_{1/2}$	J^π	E_γ(keV)
162 g	8.2 min		402.8 441.6
m			
161 g	3.6 min	$5/2^-$	
m			
160 g	∞	0^+	
m			
159 g	18.6 h	$3/2^-$	363.7
m			
158 g	∞	0^+	
m			
157 g	∞	$3/2^-$	
m			
156 g	∞	0^+	
m			
155 g	∞	$3/2^-$	
m			
154 g	∞	0^+	
m			
153 g	241.6 d	$3/2^+$	
m			
152 g	∞	0^+	
m			
151 g	120 d	$7/2^-$	
m			
150 g	10^6 y	0^+	
m			
149 g	9.5 d	$7/2^-$	149.2 298.5
m			
148 g	~90 y	0^+	
m			
147 g	38.1 h		
m			
146 g	48.3 d	0^+	
m			
145 g	21.8 min		
m	85 s		

In the spectrum of gamma-rays produced in negative pion capture the gamma-lines of ^{160}Tb, ^{162}Tb and ^{163}Tb isotopes have been reliably identified. The isotopes of ^{154}Tb and ^{156}Tb have also been found. In the gamma-ray spectrum we observe 123.1, 247.9, 392.9 *KeV* gamma-lines of the ^{154}Tb isotope as well as 88.9, 199.2, 356.5, 534.3, 1221.4 and 1384 *KeV* gamma-lines of the ^{156}Tb isotope.

However, we could not determine reliably to what of the metastable states of ^{154}Tb and ^{156}Tb the observed transitions refer.

3. DISCUSSION OF RESULTS

3.1. Neutron Multiplicity and Isotope Yields in the $(\pi^-; xn, yp)$ *Reaction*

The experimental measurements of neutron energy spectra and the determination of the yields of various isotopes in pion capture by nuclei made it possible to establish that in the spectrum of emitted neutrons two compounds are clearly distinguished, namely, fast neutrons and "evaporational" ones. Such a character of neutron spectra shows vividly that two mechanisms are responsible for neutron emission, namely, pion absorption by clusters and evaporation of neutrons produced by the complex nucleus.

It should also be noted that all the available data on neutron emission have been obtained, mainly, for spherical nuclei and that the average number of emitted neutrons is increased from 2 to 10 with increasing the atomic number from 6 to 92.

The majority of nuclei in the region under study are axially symmetric and an alongated rotational ellipsoid is their equilibrium shape. The calculated parameters of equilibrium deformation on β°_{20} for these nuclei are in the range from 0.2 to 0.35.

As has been supposed, the deformation of the initial nucleus does not affect the general character of neutron emission. *Figure 6* shows the Ho isotope yield in relative units. It is seen that in pion capture by deformed nuclei the isotopes are produced in a wide range of masses, i.e., the emitted particle distribution is not narrow but sufficiently wide, from 2 to 14.

The average number of neutrons emitted in pion absorption by deformed nuclei is 8-9 particles. This result does not contradict the data obtained by direct detection of the neutron number /5,6/ and agrees with our results obtained earlier for spherical nuclei /1/. Thus, the average number of emitted neutrons in the ^{175}Lu(π^-, xn) and ^{165}Ho(π^-, xn) reactions is $\bar{x} = 6$ /5/ while in the ^{197}Au(π^-, xn) reaction is $\bar{x} = 6.5$/6/ for ^{208}Pb $\bar{x} = 8 - 9$ /1/.

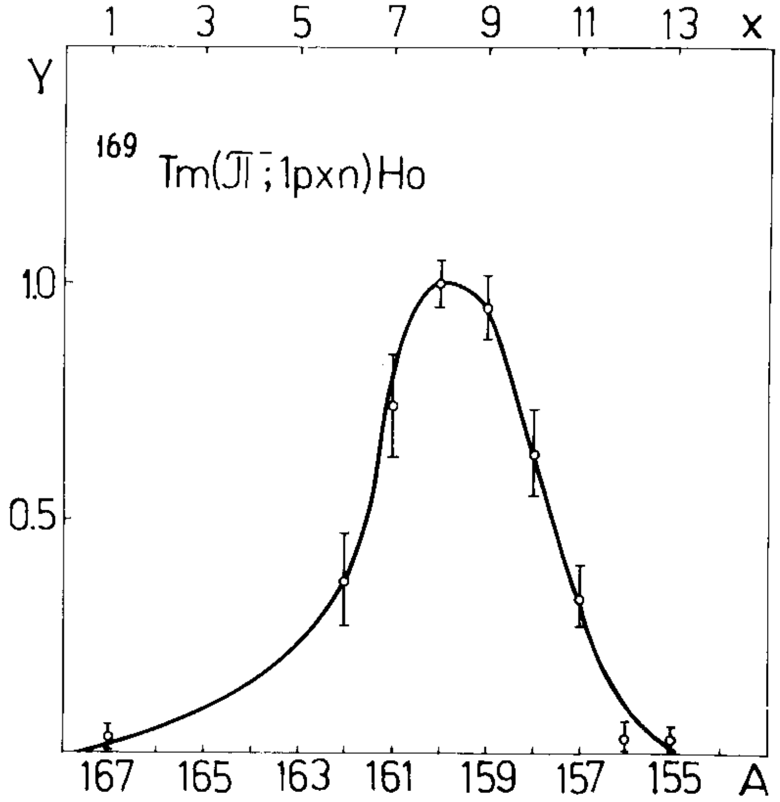

Fig. 6. A relative yield of Ho *isotopes produced in the negative pion capture by* Tm *nuclei.*

In the distribution of Tl isotope yields in the $^{208}Pb(\pi^-, xn)$ reaction we have noticed two separated maxima with A=197 and A=201 /1,4/. According to the calculation of A.S.Ilyinov and S.E.Chigrinov /15/, this structure and yield distribution is due to two pion absorption mechanisms (a quasideutron and alphaparticle ones).

In deformed nuclei (*Fig. 6*) no similar structure in the distribution of Ho isotope yields is observed.

This may imply that the study of product yields in pion interaction with nuclei makes it possible to establish a ratio of pion absorption on quasideuteron and alphaparticle clusters.

The calculation data by A.S.Ilyinov and S.E.Chigrinov /15/ obtained under the assumotion that 25% of all interaction events are alpha-particle clusters, while 75% are quasideuteron clusters provide good agreement with the experimental results for ^{208}Pb /1,4/.

However, in the case of a ^{169}Tm target, calculations have significant discrepancy in the region of small x values. According to calculations the compound-nucleus produced after pion absorption turns out to be excited up to high energies when absorbed by an alpha-cluster. In this case a great number of neutrons are evaporated and as a result lighter isotopes are produced. It is quite possible that in nuclei with a large mass number A the alpha-particle mechanism of negative pion absorption is less important. With decreasing the A number or the total number of particles in the nucleus, the role of the alpha-particle absorption mechanism is considerably decreased. This conclusion is confirmed experimentally. Thus, a low yield of high energy tritons in negative pion absorption by ^{59}Co, ^{75}As and ^{197}Au /7/ nuclei can be explained by a small probability of the alpha-particle absorption mechanism.

3.2. *Excitation of High Spin States and the Texture of Nuclear Surface*

The excitation of rotational nuclear motion in the capture of negative pions at rest has been demonstrated on spherical nuclei in the region of Z=50 /2/ and Z=82 /3,4/. The $^{177m_2}Hf$ (37/2) isomer has a large spin value among nuclei under investigation.

Our systematic studies have shown (see *Tables 1-5*) that for the whole region of nuclei under investigation the states with sufficiently high spins have been observed. For example, the isomers of ^{158m}Ho and ^{160m}Ho with spins 9^+, $^{162m}Ho(6^-)$, etc., are produced with greater probability.

Usually, to show how effectively isomers are produced the probability of isomer production is normalized to that of nucleus production in the ground state. This value is an isomer ratio.

Table 6 presents the experimental values of isomer ratios obtained by us for Ho isotopes. As is seen from

Table 6

Isomeric ratios in the $^{169}Tm(\pi^-, pxn)$ and $^{166}Er(\pi^-, xn)$ reactions

Reaction	Isotope	σ_m/σ_g	Ground State		Isomeric State		σ_m/σ_g of other reactions
			I^{π}	E_{γ}(KeV)	I^{π}	E_{γ}(KeV)	
$^{169}_{68}Tm(\pi^-, p10n)$	$^{158}_{67}Ho$	0.35±0.07	5^+	994.4	2^-	425.4	
$^{169}_{68}Tm(\pi^-, p10n)$	$^{158}_{67}Ho$	1.25±0.25	5^+	994.4	9^+	406.5	
$^{169}_{68}Tm(\pi^-, p10n)$	$^{158}_{67}Ho$	5.26±0.89	2^-	425.4	9^+	406.5	0.02-(Ta+p) /15/ 0.025-^{162}DY+p
$^{169}_{69}Tm(\pi^-, p8n)$	$^{160}_{67}Ho$	1.39±0.29	5^+	645.4	9^+	966.2	
$^{169}_{68}Tm(\pi^-, p6n)$	$^{162}_{67}Ho$	3.6±0.6	I^+	1319.6	6^-	1220.0	
$^{166}_{68}Er(\pi^-, 4n)$	$^{162}_{67}Ho$	1.3±0.3	I^+	1318.6	6^-	1220.0	

the *Table*, in a great number of cases the isomeric ratio is larger than unity, i.e., the probability of isotope production in the isomeric state with high spin is many times greater than that in the ground state. The isomeric ratio is smaller than unity $\xi = \sigma_m / \sigma_g =$ (0.35±0.07) when the spin of the metastable state $^{158m_1}Ho(2^-)$ is smaller than that of the ground state $^{158g}Ho(5^+)$.

When the isomeric spin is higher than the ground state spin the isomeric ratio is larger than unity. For example, for ^{158m}Ho $\sigma_{m_2}(9^+)/\sigma_g(5^+) = (1.15 \pm 0.25)$; $\sigma_{m_2}(9^+)/\sigma_{m_1}(2^-) = (5.26 \pm 0.89)$.

It is worth noting that the $^{158m_2}Ho$ isomeric yield in the deep spallation reaction is 0.02% of the $^{158m_1}Ho$ isomeric yield according to ref./15/. This is nearly two orders of magnitude smaller than the value obtained by us in the absorption reaction of negative pions at rest.

If in the deep spallation reaction $^{181}Ta(p;\ 7p,\ 17n)$ the isotope ^{158}Ho can be produced in the emittance of 24 nucleons, then this isotope can be produced in pion capture $^{169}Tm(\pi^-, p10n)^{158}Ho$ in the emittance of 11 nucleons.

It is clear, that the isomeric ratio in the deep spallation reaction for ^{158}Ho must be smaller than that for negative pion absorption.

It is worth noting that the isomeric ratio for ^{162}Ho produced in the $^{169}Tm(\pi^-, p6n)$ and $^{166}Er(\pi^-, 4n)$ reactions is as follows:

$$\sigma_m/\sigma_g = (3.6 \pm 0.6) \text{ and } \sigma_m/\sigma_g = (1.3 \pm 0.3).$$

This result shows that 1) the excitation of nuclear rotational motion is possible both in proton and neutron emission, and 2) the probability of high spin isomer excitation depends upon the number of emitted nucleons, as predicted by theory /15/. The isomeric ratio is first increased with increasing nucleon emission from 2 to 8, then it is reduced in further increasing the number of emitted particles /15/.

Thus, one can consider that the isomeric ratio depends both upin energy and spin of the levels of produced states and upon the number of emitted particles and, to a greater extent, upon the total number of nucleons participating in the formation of these states.

And last but not least, since nuclei under investigation are strongly deformed, the obtained results show that the excitation of the rotational motion is weakly dependent on the mass, charge and deformation of the initial nucleus, but is due mainly to pion absorption on nucleon clusters.

Another possibility of studying the production mechanism of high spin as well as the texture of the nuclear surface appeared due to the measurements of isobaric ratios. The isobaric ratio is a ratio of independent yields (production cross sections) of two isobar nuclei.

In the experiment we have measured the ratio of the independent yield of ^{159}Er (36 *min*) and ^{159}Ho (33 *min*) in $^{169}Tm(\pi^-, xn)$ and $^{169}Tm(\pi^-, pxn)$ reactions, respectively. The value of the isobaric ratio found by the yield of the most intensive gamma-transitions of these isotopes is $I = (9.9 \pm 2.9)$.

To connect the value of the isobaric ratio with the nuclear surface texture we have considered only the basic reaction channels resulting in ^{159}Er and ^{159}Ho production. This is possible to perform since the alpha-particle absorption mechanism, as has been shown, has relatively small probability.

Consequently, the ^{159}Er isotope can be produced in the quasi-deuteron absorption, i.e., in the $(\pi^- np \to nn)$ process with the further absorption of one of neutrons and in the $(\pi^- pp \to pn)$ process and a further absorption of a proton.

The ^{159}Ho isotope was produced in the $(\pi^- pp \to np)$ process with neutron absorption.

Thus, considering the quasideuteron mechanism as the basic mechanism of pion absorption in the nucleus we can establish the correlation between the experimental value of isobaric ratio (I) and the ratio of the number of np and pp clusters on the nuclear surface: $R = N_{np}/N_{pp} = (4.4 \pm 1.1)$. The value $R = (4.4 \pm 1.1)$ obtained for deformed ^{169}Tm nucleus agrees well with the result $R = (5.0 \pm 2.8)$ obtained earlier for ^{209}Bi /16/.

These results show vividly both the effect of the cluster structure of atomic nuclei and proves that the surface of medium and heavy nuclei is enriched mainly by np-clusters comparing to pp ones.

These conclusions make it possible to understand deeper the details of nuclear pion absorption and the excitation mechanism of nuclear rotational motion.

It becomes evident that in the absorption of negative pions at rest an additional angular momentum of the nucleus occurs in the disruption of the quasideuteron np- or pp -pairs. The energy of 140 *MeV* can be divided between these two nucleons equally, i.e., each of them acquires 70 *MeV*. It is due to these fast particles that the wide mass distributions of final nuclei and their high spins observed in the experiment appear.

Indeed, if both the nucleons emit from the nucleus without interacting with other nucleons on their way or both the nucleons are absorbed in the nucleus thus initiating an intranuclear cascade, the angular momentum of the residual nucleus will be small.

If in the disruption of np- and pp-pairs a fast nucleon emits from the nucleus, while the other one is absorbed by the nucleus, transferring its energy to other nucleons, the produced residual nucleus must rotate. The angular momentum of such a nucleus can reach the maximal values of about 15-20 $\hbar$.

When we had prepared our paper for publication we read the paper by R.Beetz et al./17/, where they thoroughly investigated the absorption of stopped pions in ^{181}Ta and ^{209}Bi by studying prompt and delayed gamma-ray spectra. The results of R.Beetz et al. agree well with our data.

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