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NEGATIVE PION CAPTURE IN ATOMIC NUCLEI NEAR THE CLOSED NEUTRON SHELL AT N=82

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1. INTRODUCTION

In recent years, great interest has been shown in the studies of π^--absorption from mesoatomic orbits because they allow us to obtain valuable information about both the mechanism of pion interactions with the intranuclear nucleon associations - clusters - and the properties of the atomic nucleus at high (up to 140 MeV) excitation energies.

With the advent of high-current accelerators - meson factories this trend of research has been developing successfully in many laboratories of the world and has become of substantial importance along with the investigations carried out using heavy ion accelerators.

The experimental studies carried out in this field at Dubna /1-4/, SIN /5,6/, CERN /7,8/ and Los Alamos /9/ provide convincing evidence that π^--absorption in atomic nuclei gives rise to the previously unknown phenomenon of the excitation of high spin states and a large multiplicity of the emitted neutrons and charged particles.

These experiments stimulated the elaboration of a number of theoretical models. The majority of experimental results was successfully interpreted within the framework of those models which consider pion absorption to be a multi-stage process /9-12/.

As additional experimental data are needed for the further many-sided investigation of the mechanism of the excitation of high spin nuclear states by pions, it is necessary to carry out systematic studies using a large number of target nuclei and different techniques.

Since 1974 we have been performing an extensive research program in this direction by passing from one nuclear region to another. Initially we investigated the excitation of high spin statas by pions in the region of spherically symmetric nuclei /1-3/ and subsequently in the region of strongly deformed and transitional nuclei /4/ in the hope to find a difference in the processes of pion absorption in spherical, deformed and transitional nuclei.

The present paper is an extension of this research programme and deals with a study of the excitation of high spin states by pions in the nuclei of the intermediate region, N=82 (the so-called island of isomerism).

2. EXPERIMENT

The irradiation of targets was performed using a π^--beam from the Dubna synchrocyclotron. The density of π^--stops in the targets was 10^4 g^{-1} s^{-1}. After the activation, ~2 g/cm^2 targets manufactured of Nd, Pr, Ce, La and Ba were investigated using a Ge(Li) - detector with a resolution of 2.5 keV for E_γ =1332.5 keV of ^{60}Co. The treatment of γ-ray spectra was performed on BESM-6 and CDC-6500 computer using standard codes. A more detailed description of the activation technique is given in refs./1-4/. The typical γ-ray spectra of the isotopes formed as a result of the π^--irradiation of the Nd, Pr, Ce, La and Ba targets are shown in figs. 1-5.

3. THE IDENTIFICATION OF HIGH SPIN ISOMERS

As is seen from figs. 1-5, the γ-lines due to a number of the high spin isomers of Pr, Ce, La, Ba, Cs and Xe have been identified in the γ-ray spectrum of the isotopes produced in the reaction (π^-;yp, xn) (the γ-ray energies of the corresponding isotopes are indicated with numbers in the figures). Information about the high spin isomers (spins and half-lives) is given in the Table.

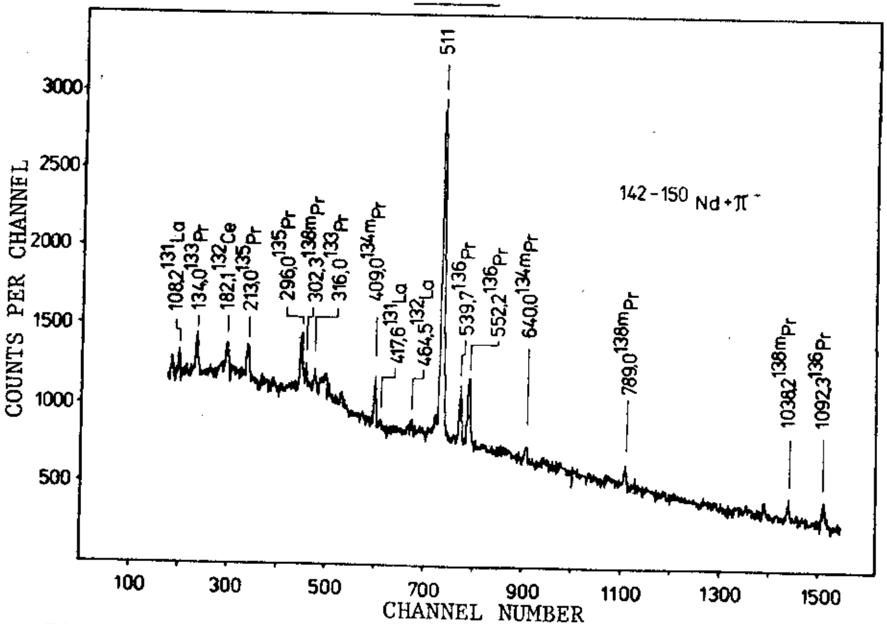

Fig. 1. The γ-ray spectrum of the Pr, Ce and La isotopes formed in the pion bombardment of a Nd target.

Table

The observed high spin isomeric states in the nuclides formed in the reaction (π^-:xn,yp)

Target nucleus, Z^A	I_i	(π^-,xn)	(π^-,pxn)	(π^-,2pxn)
$^{142-150}_{60}$Nd	(0^+,$7/2^-$)	$^{138m}_{59}$Pr(7^-; 2.1 h)	—	—
$^{141}_{59}$Pr	($5/2^+$)	$^{137m}_{58}$Ce($11/2^-$;34.4 h)	—	$^{137m}_{56}$Ba($11/2^-$;2.55min) $^{135m}_{56}$Ba($11/2^-$;28.7h) $^{133m}_{56}$Ba($11/2^-$;38.9h) $^{131m}_{56}$Ba($9/2^-$;14.6min)
$^{140}_{58}$Ce	(0^+)	$^{132m}_{57}$La(6^-;24.3 min)	$^{133m}_{56}$Ba($11/2^-$;38.9 h) $^{131m}_{56}$Ba($9/2^-$;14.6min)	—
$^{139}_{57}$La	($7/2^+$)	$^{137m}_{56}$Ba($11/2^-$;2.55min) $^{135m}_{56}$Ba($11/2^-$;28.7 h) $^{133m}_{56}$Ba($11/2^-$;38.9 h) $^{131m}_{56}$Ba($9/2^-$;14.6 min)	$^{135m}_{55}$Cs($19/2^-$;53 min) $^{134m}_{55}$Cs(8^-;2.9 h)	—
$^{138}_{56}$Ba	(0^+,$3/2^+$)	$^{135m}_{55}$Cs($19/2^-$;53 min) $^{134m}_{55}$Cs(8^-;2.9 h)	$^{135m}_{54}$Xe($11/2^-$;15.6min)	—

The fact of observation and identification of high spin isomers according to intense γ-lines suggest that the high spin states are excited effectively at the absorption of negative pions not only in spherical and strongly deformed nuclei, but also in the transitional nuclei lying near closed neutron shell $N=82$.

We shall consider these reactions in more detail.

3.1. The High Spin Isomers of Ba

In the pion bombardment of Pr, Ce and La targets with natural isotopic composition, the formation of the high spin Ba isomers $^{131m}Ba(9/2^-)$, $^{133m}Ba(11/2^-)$, $^{135m}Ba(11/2^-)$ and $^{137m}Ba(11/2^-)$ have been detected. These high spin states cannot be populated through the β-decay of lanthanum or cesium isotopes and, therefore, have been identified as the direct products of the reaction $(\pi^-; yp, xn)$.

The formation of the isomer $^{131m}Ba(9/2^-)$ in the reaction involving π^--absorption in the nuclei ^{139}La and ^{141}Pr whose spins are equal to 7/2 and 5/2, respectively, can in principle be accounted for by the algebraic sum of the initial nuclear spin and the pionic orbital momentum $\ell=2h$. However, in poin capture reactions on cesium nuclei with zero spin, it is impossible to explain simply by the statistical distribution of the angular momenta of the compound system, the observation of the product nucleus ^{131m}Ba with spin 9/2 that exceeds nearly twice the initial angular momentum of the system. It is still more difficult to explain by the algebraic sum of the momenta of the pion and initial nucleus the formation of the high spin isomers ^{133m}Ba, ^{135m}Ba and ^{137m}Ba with spin $I^{\pi}=11/2^-$ which exceeds the initial angular momentum by a factor of three. This fact can be explained only in terms of the twisting mechanism suggested in ref. /10/, which implies the twisting of the nucleus by the emitted fast nucleons formed as a result of the breakup of np or pp quasideuteron pairs followed by the intranuclear cascade.

An exception may be the formation of ^{137m}Ba in the reaction $^{139}La(\pi^-, 2n)\,^{137m}Ba$, in which two neutrons from the direct reaction $(\pi^- + np \rightarrow nn)$ escape the nucleus in opposite directions imparting no additional angular momentum. In this case the excitation of the isomer $^{137m}Ba(11/2^-)$ can be accounted for by the simple sum of the momenta of the initial nucleus and the π^--orbital momentum.

In a slow π^--capture reaction, the issomeric ratio σ_m/σ_q can serve as a measure of the intensity of populating nuclear high spin states. At present the amount of available data on

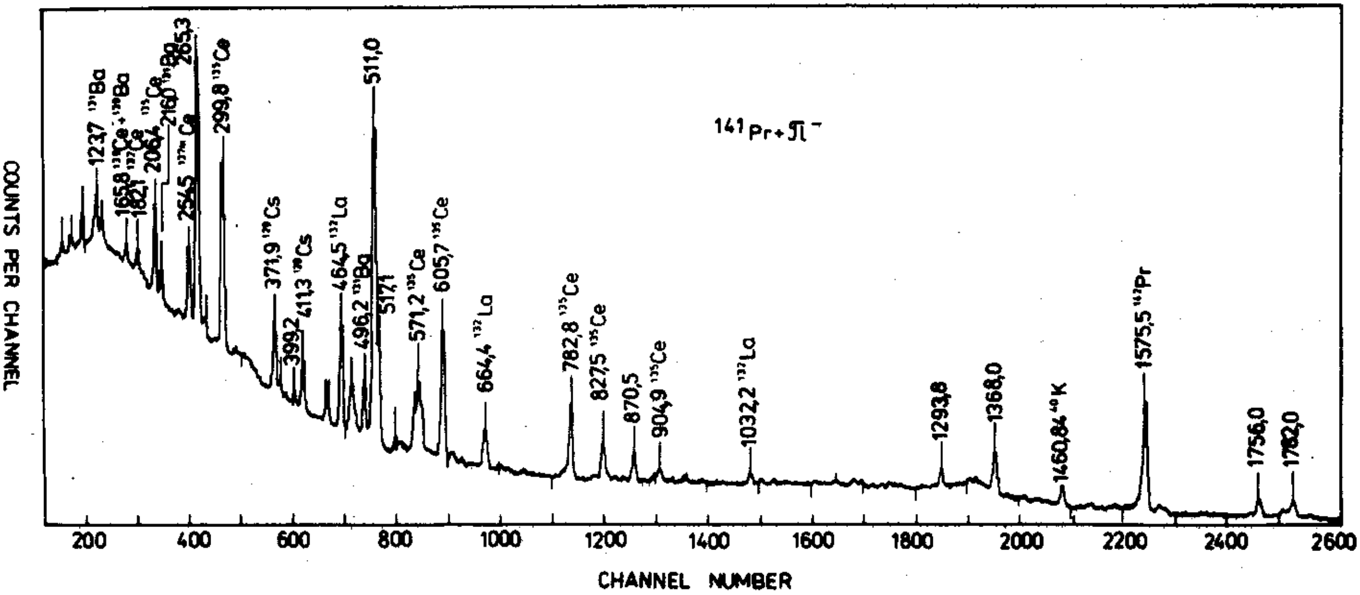

Fig.2. The γ-ray spectrum of the Ce, La, Ba and Cs isotopes formed at π^--absorption in Pr target nuclei.

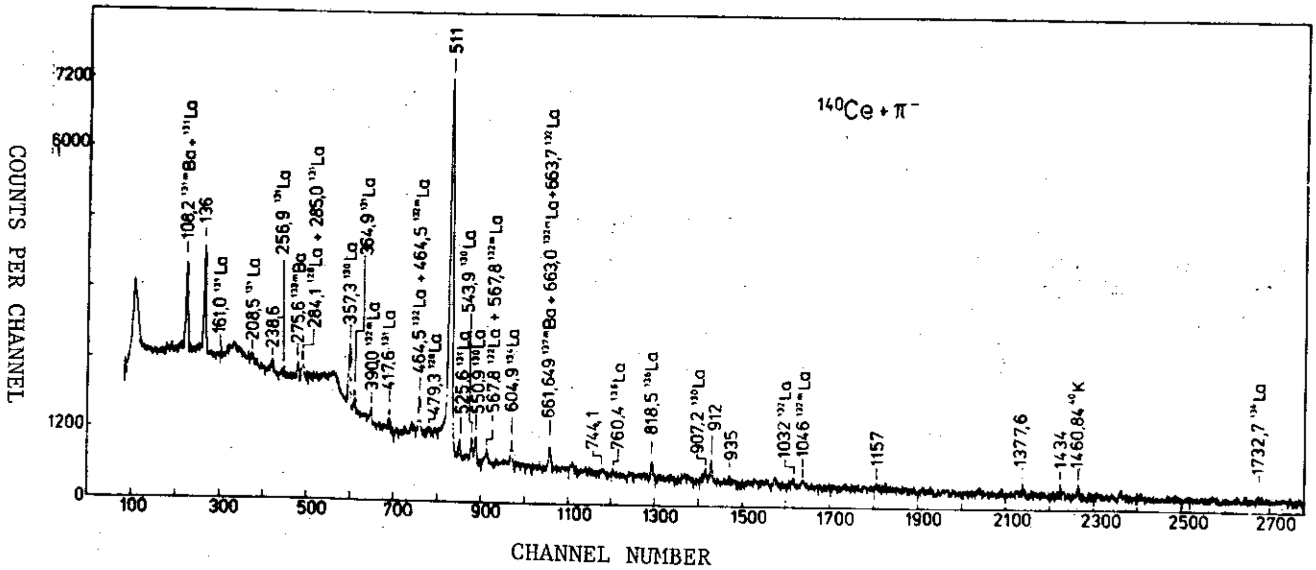

Fig.3. A typical γ-ray spectrum of the La, Ba and Cs isotopes formed in the reaction $(Ce+\pi^-)$.

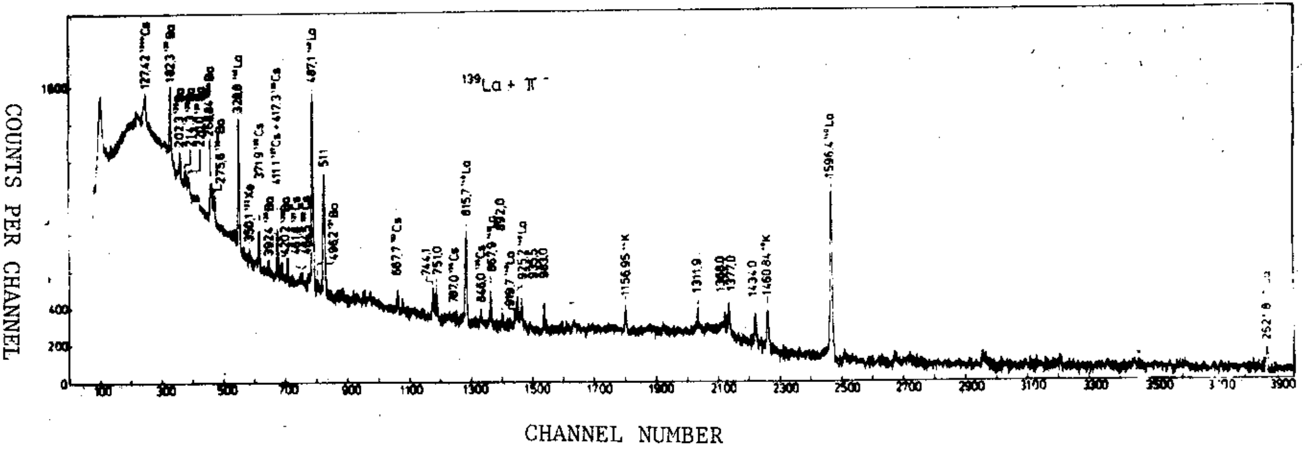

Fig.4. The γ-ray spectrum of the Ba, Cs, Xe and I isotopes formed in the reaction ($La+\pi^-$).

the value of the isomeric ratios is not large. From experiments with nuclei in the region of Z=50, Z=82 and Z=70 (refs./2-4/) it is known that the value of the isomeric ratio can reach several units. For instance, for the reaction $^{208}Pb(\pi^-, 10n)^{198m}Tl$ it has been found to be $\sigma_m/\sigma_g=5.0$./1/ In addition, it is known /13/ that the isomeric ratio depends on the number of the particles emitted.

In the present paper isomeric ratios have been determined for two types of reactions. In the first reaction, at pion absorption in the nucleus ^{139}La only neutrons are emitted leading to the formation of the isotope ^{131}Ba in metastable and ground states with spins $I^\pi = 9/2^-$ and $I^\pi = 1/2^+$, respectively. In the other reaction, the emission of one proton and several neutrons occurs leading to the formation of the isotope ^{133}Ba in metastable and ground states with spin $I^\pi = 11/2^-$ and $I^\pi = 1/2^+$, respectively. For the reaction $^{139}La(\pi^-, 8n)^{131m,g}Ba$ the following isomeric ratio has been obtained:

$$\sigma_m/\sigma_q = \frac{Y\ ^{131}Ba(9/2^-)}{Y\ ^{131}Ba(1/2^+)} = (5.1 \pm 0.5).$$

For the reaction $^{140}Ce(\pi^-; p, 6n)^{133m,g}Ba$, the isomeric ratio has been determined to be as follows:

$$\sigma_m/\sigma_g = \frac{Y\ ^{133}Ba(11/2^-))}{Y\ ^{133}Ba(1/2^+)} = (2.2 \pm 0.3).$$

These results show that the residual nuclei ^{131}Ba and ^{133}Ba formed as a result of π-absorption in the nuclei ^{139}La and ^{140}Ce have received fairly large angular momentum.

3.2. The High Spin Isomers of Cesium

The high spin isomers $^{134m}Cs(8^-)$ and $^{135m}Cs(19/2^-)$ have been detected among the reaction products formed in the bombardment of lanthanum and barium targets. These isomers cannot be populated through the β-decay of the neighbouring nuclei either, and have been identified to be the products of the reactions $^{139}La(\pi^-, p4n)$ and $^{136-138}Ba(\pi^-; 2\text{–}3n)$, respectively. These isomers are discharged by pure isomeric transitions, which are identified in the γ-ray spectra unambiguously (see figs. 4 and 5).

The isomer ^{134m}Cs has been identified according to the 127.5 keV line. The half-life determined from the decreasing intensity of this line is equal to ~3 hours and agrees with the previously measured values /14/. This confirms the correctness of identification of the isomer ^{134m}Cs.

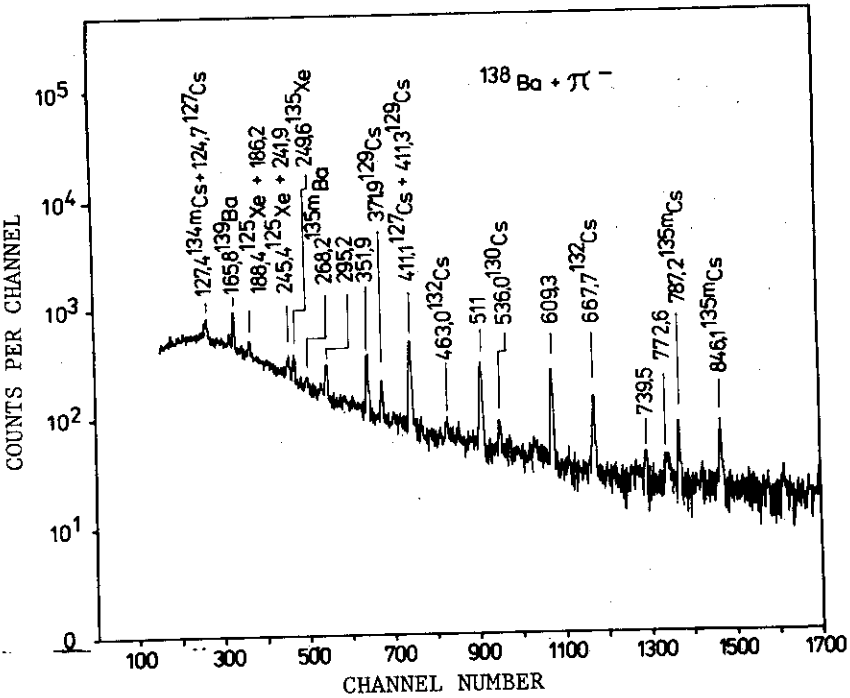

Fig.5. The γ-ray spectrum of the Cs, Xe, I and Te isotopes formed in the reaction (Ba+π^-).

The isomer ^{135m}Cs has been identified according to the two γ-lines with energies of 787.2 keV and 846.1 keV, the intensity of which decreased with the half-life $T_{1/2}$ =53 min (see fig. 6). This result agrees with the $T_{1/2}$ measurements of the isomer ^{135m}Cs from other reactions /14/.

As the isotopes ^{134}Cs and ^{135}Cs live in the ground state long - $T_{1/2}$ =2 years and $T_{1/2}$ =2 million years, respectively - it is impossible to determine their isomeric ratios.

However, by determining experimentally the independent yields of the isotopes with close spin and their ratios one can establish the dependence of the probability of populating states for different numbers of the particles emitted.

Experimentally, we have found the isotopic ratio for the reactions ^{139}La(π^-,p3n) ^{135m}Cs(19/2$^-$) and ^{139}La(π^-;p4n)^{134m}Cs(8$^-$) from the yield of the 127.5 keV γ-lines due to the isomer ^{134m}Cs and of the 787.2 keV γ-line due to the isomer ^{135m}Cs. The value of the isotopic ratio

$$K = \frac{\sigma(^{134m}Cs)}{\sigma(^{135m}Cs)}$$

has been determined to be equal to (9.8 ± 2.3) taking into account the efficiency of the Ge(Li) detector, γ-ray self-absorption in the targets and time factors.

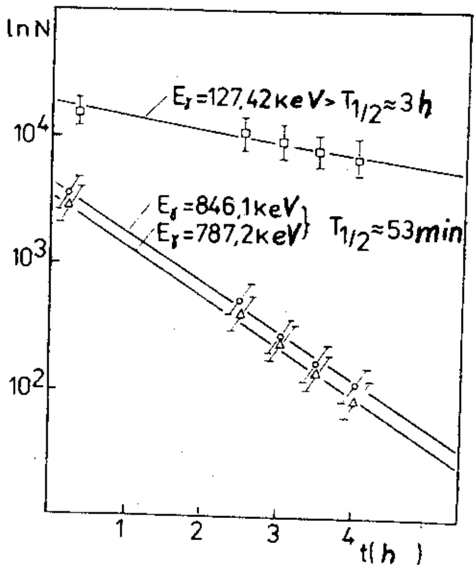

Fig.6. Determination of the half-lives of the isomers ^{134m}Cs from the decreasing intensity of the 127.42 keV γ-lines and ^{135m}Cs from the decreasing intensity of the 787.2 keV and 846.1 keV γ-lines.

3.3. The High Spin States in Pr, Ce, La and Xe

The Nd target contains 80% of nuclei (A =142, 144, 146, 148, and 150) with zero spin and 20% of nuclei (A=143 and 145) with spin $I^\pi = 7/2$. Therefore the formation of the high spin state of ^{138m}Pr(7^-) in the reaction Nd(π^-, xn) can be explained by assuming that the product nucleus has received large additional angular momentum during the process of pion absorption on a quasideuteron.

The formation of the isomer ^{137m}Ce ($11/2^-$) in the reaction Pr(π^-,4n) is of inconsiderable interest since the spin of the initial Pr nucleus is equal to 5/2.

The Ce target contains only even-even isotopes with zero spin and the formation of the isomer ^{137m}La (6^-) in the reaction Ce(π^-,xn) shows that the spin of the residual nucleus, in pion capture reaction, exceeds at least three times the initial momentum of the pionic-nuclear system.

The isomer ^{135m}Xe($11/2^-$) can be formed as a result of pion absorption in the barium isotopes ^{137}Ba (11%) with spin $I^\pi = 3/2^+$ and ^{138}Ba (71%) with spin $I^\pi = 0$ followed by the emission of one proton and several neutrons in the reaction Ba(π^-,pxn). This result shows that additional angular momentum of the residual nucleus can be produced by the emission from the nucleus of any nucleon of the quasideuteron pair, irrespective of its electric charge.

4. DISCUSSION

The experimental results obtained in the present paper show that π^--absorption in nuclei with the closed neutron shell N =82 leads to the intensive excitation of high spin nuclear states (see the Table). In addition, the experimental data obtained earlier in the studies of π^--absorption in spherical nuclei with closed shells (Z =50, Z =82 and N =126) and in strongly deformed nuclei indicate that the phenomenon of high spin state excitation does not depend of the properties (mass, deformation, shell structure, etc.) of the nucleus on which the absorption occurs. The results of the present paper are in agreement with these conclusions and confirm that the excitation of high spin states is associated mainly with the mechanism of pion absorption. The versatility of the phenomenon of high spin state excitation is related to the primary event of pion absorption on np and pp quasideuteron pairs in the surface layer of the nucleus.

In this process, additional angular momentum is transferred to the residual nucleus at the initial stage when fast nucleons are emitted from the nucleus. Therefore it is illegitimate to compare the excitation of high spin states in residual nuclei by stopped pions with the reactions induced by fast projectiles.

One can compare the second (cascade-evaportation) state of pion absorption in a nucleus with spallation reactions, in which the particles evaporated can only change to some extent the angular momentum of the nucleus. Therefore the results of ref./15/, in which an extremely small value of the isomeric ratio has been obtained for ^{158}Ho in the reaction (Tm+π^-) and a conclusion has been drawn that in slow π^--induced reactions no predominant excitation of high spin states has been observed are doubtful.

In addition, the value of the isomeric ratio (σ_m/σ_g = =5.26)/4/ for ^{158}Ho, obtained for the same reaction (Tm+π^-) agrees well with the existing experimental data on the isomeric ratios from reactions initiated by pions on a large number of nuclei (see, e.g., review /16/).

Of course, the value of the isomeric ratio depends largely on the spin values of the states compared and may have a small value in separate cases. For instance, in ref./17/ the authors compare the value of the isomeric ratio for the reaction $^{93}\mathrm{Nb}(\pi^-,\mathrm{p6n})^{86m,g}\mathrm{Y}$, $\sigma(8^+)/\sigma(4^-)=(0.90\pm0.12)$, with the isomeric ratio for the reaction $^{89}\mathrm{Y}(\mathrm{p,p3n})^{86m,g}\mathrm{Y}$ which is equal to $\sigma(8^+)/\sigma(4^-)=(0.45\pm0.07)$. On the other hand, for the reactions $^{93}\mathrm{Nb}(\mathrm{p,p5n})^{87m,g}\mathrm{Y}$ and $^{89}\mathrm{Y}(\mathrm{p,p2n})$

$^{87m,g}Y$ the isomeric ratios have been obtained to be $\sigma_m(9/2)/\sigma_g(1/2)=(8\pm2)$ and $\sigma_m(9/2)/\sigma_g(1/2)=(2.05\pm0.02)$, respectively.

The results obtained can be easily interpreted. In the case where the spins of the states being compared differ by a factor of two (8^+ and 4^-), the isomeric ratios for reactions involving pions and protons are comparable and have small values. In the case where the spins of the states differ by a factor of 9-(9/2 and 1/2) the isomeric ratio is by a factor of 4 larger in pion induced reactions than in reactions initiated by protons.

This indicates that at the end of the cascade-evaporation stage of the pion capture reaction nuclear levels with higher spins are excited compared with proton induced spallation reactions, and the electromagnetic transitions that obey the strict selection rules are expected to lead to different values of the isomeric ratio. Naturally this difference should depend on the difference between the spins of the metastable and ground states. Therefore, on the basis of the value of the isomeric ratio for states with close spin it is impossible to draw the conclusion that pion capture reactions and spallation reactions are similar in the process of the excitation of high spin states because the physical causes of the excitation of these states are different. In slow pion capture reactions the product nucleus receives additional angular momentum at the initial stage when a fast nucleon escapes as a result of the breakup of the quasideuteron pair, whereas this stage is absent in spallation reactions.

Similarly, in a spallation it is impossible to excite states with spins as high as those in heavy ion reactions, although even close isomeric ratios can be obtained for states with low spins.

As is shown above, in the reaction $^{139}La(\pi^-,pxn)$ the ratio of probabilities of populating the high spin isomers ^{134m}Cs and ^{135m}Cs which have approximately identical spin values, $I^\pi=8^-$ and $I^\pi=19/2^-$, respectively, turned to be equal to $K=(8.9\pm2.3)$.

This strong difference on the excitation probability for the high spin isomers of the neighbouring isotopes of cesium ($\Delta A=1$) is at variance with the data of ref. /8/ in which the probability of populating various spin states in Hf isotopes in the reaction $Ta(\pi^-,xn)$ has been found from the intensity of prompt γ-transitions between the levels of the residual nucleus.

In ref.[8] the probability of populating the levels of the same isotope depends exponentially on their spins. However, if we consider the total probabilities of populating states with spins above 8h, then the values of probabilities for adjacent even isotopes of Hf ($\Delta A = 2$) differ from each other not as strongly as do the values of probabilities for two neighbouring isotopes of cesium ($\Delta A = 1$) obtained in the present paper. The independent yields of high spin isomers we determine are virtually the cumulative yields of all high spin states that decay to these isomeric states through a fast γ-ray cascade.

Naturally, the level structure of even and odd nuclei can differ strongly and, therefore, the observed discrepancy can be related to the structural features of the residual nuclei. The isotopic effect of the excitation of high spin states during the process of slow π^--absorption is subject to further investigations.

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