Excitation of high-spin states during negative-pion absorption by atomic nuclei

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In this review experimental data are presented on the excitation of high-spin isomer states as a result of absorption of slow negative pions by atomic nuclei and the mechanism whereby such states are excited is discussed.

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CONTENTS

1. INTRODUCTION

It is well known that the interaction between stopped negative pions and nuclei occurs via a stage involving the formation of π-mesic atoms.

Transitions from states in the continuous energy spectrum to the discrete levels of a π-mesic atom result in the pion entering levels with high principal quantum numbers. The pion then descends by electromagnetic transitions to lower-lying levels, with a smaller value of the principal quantum number. In the very lightest elements, the pion eventually ends up in the 1s level from which it is absorbed by the nucleus.

A different situation occurs in the case of π-mesic atoms of heavy elements. Here, the atomic orbits are much closer to the nucleus, so that the pion occupying a level above the 1s state begins to experience not only the electromagnetic but also the strong interaction with the nucleus. The point is that, in π-mesic atoms of heavy elements, the pion repeatedly crosses the surface of the nucleus even in the 4f orbit. The result of this is that the nucleus absorbs the pion before the latter succeeds in descending to levels lying below the 4f state.

Measurements on γ rays emitted as a result of pion transitions between the levels of π-mesic atoms of heavy elements have shown that the 4f-3d, 3d-2p, and 2p-1s transitions are absent from the γ-ray spectrum.

The strong pion-nucleus interaction is the reason for the observed level broadening and shift. According to modern ideas, the absorption of a negative pion from an orbit in the mesic atom occurs as a result of the interaction between the pion and the nucleon clusters in the nucleus, i.e., nucleon associations which appear for short periods of time on the nuclear surface.

The question of the existence of two-nucleon clusters arose after the experiments by M. G. Meshcheryakov *et al*,[1] who found that the interaction between protons with energies of a few hundred MeV and target nuclei is accompanied by emission of deuterons.

Wilkinson[2] subsequently analyzed the data on the spectrum of hyperons emitted during the interaction between negative kaons and nuclei, and drew attention to the fact that the nuclear surface was enriched with two-nucleon clusters.

In the kaon-nucleon interaction, the reaction proceeds as follows:

$$K^- + N \to \Sigma + \pi, \quad Q = 100 \text{ MeV}.$$

If, on the other hand, the reaction occurs on the two-nucleon association, the pion is not produced, i.e., the process is

$$K^- + 2N \to \Sigma + N, \quad Q = 230 \text{ MeV}.$$

In the latter case, the energy of the Σ particles is found to be higher than in the interaction with one nucleon, and experiments have, in fact, demonstrated that the Σ-particle spectrum contains an excess of high-energy Σ particles.

Existing experimental data on negative-pion absorption by nuclei also indicate that nucleon associations play an important role.

It is well known that absorption of negative pions by nuclei occurs in the following processes:

$$\pi^- + 2N \to 2N, \quad \pi^- + 4N \to 4N.$$

Data on correlations accompanying the emission of two neutrons from a nucleus that has absorbed a pion, and data on the emission of charged particles, may serve as experimental confirmation of the fact that the above processes play an important role in negative-pion capture.

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The capture of a pion by a nucleus is accompanied by the release of energy equal to the pion mass, i.e., approximately 140 MeV. If capture occurs on the np pair, two neutrons of 70 MeV each are produced. These neutrons are emitted in opposite directions. A certain energy spread is found to occur around 70 MeV because of the internal motion of the nucleons in the nucleus. Experiments[3-5] have confirmed the existence of correlated neutron pairs, and this may be regarded as evidence for the two-nucleon mechanism in pion absorption.

Experiments in which the energy of the charged particles was measured have shown that the spectrum contains a considerable number of protons, deuterons, and tritium nuclei with energies of a few tens of MeV.[6] This can again be understood in terms of the following pion absorption processes:

$$\pi^- + pp \to p + n,$$

$$\pi^- + {}^4\mathrm{He} \begin{cases} \to p + 3n, \\ \to d + 2n, \\ \to T + n. \end{cases}$$

Recent experiments on the synchrocyclotrons at the Joint Institute for Nuclear Research at Dubna and at SIN have resulted in the discovery of a new manifestation of the capture of negative pions by nucleon associations. This effect involves the excitation of high-spin nuclear states.[7-9]

In the Dubna experiments, it was found that excitation of metastable nuclear states with spins up to $15\hbar$ took place with appreciable probability after pion absorption. The probability of excitation of such states frequently exceeds by a substantial factor the probability of formation of the nucleus in the ground state with a lower spin. Work performed at SIN has shown that the capture of negative pions by deformed atomic nuclei (for example, Ho and Lu) is accompanied by appreciable excitation of rotational levels with spins up to $12\hbar$.

At first sight, these two effects are almost impossible to understand. In fact, the spin of the pion is zero and the $4f$ state from which the pion is captured by the heavy nucleus has an angular momentum of $3\hbar$. In actual fact, the origin of the effect can be found in the dominant role of pion capture by two- or four-nucleon associations. We have already noted that pion capture by np or pp pairs is accompanied by the transfer of an average energy of 70 MeV to each nucleon. If we then imagine that one of the nucleons is emitted along a tangent to the nuclear surface and the other remains in the nucleus and transfers its energy to other nucleons, we can readily see that the nucleus will begin to rotate and its angular momentum will, of course, be equal to the nucleon angular momentum, i.e., $M = p \cdot R$, where p is the momentum and R the nuclear radius. The result of this is that the angular momentum of an intermediate or heavy nucleus after the escape of the 70-MeV neutron may attain values up to about $15\hbar$. In practice, the emission of a fast nucleon may also leave the nucleus in a state with a *lower* angular momentum.

At any rate, the appearance of nuclear rotations can be explained in terms of existing ideas on pion capture by nucleon associations.

2. EMISSION OF NEUTRONS ACCOMPANYING NEGATIVE-PION CAPTURE BY NUCLEI

Most of the information on neutrons emitted as a result of negative-pion capture by nuclei has been obtained as a result of measurements on the energy spectra[10-13] and on the yield of different isotopes after pion capture by nuclei.[14-19]

Figure 1 shows the energy spectrum of neutrons, obtained by the time-of-flight method. It is clear that, while the spectrum contains neutrons with energies of a few tens of MeV, most of them have much lower energies.

This shape of the neutron spectrum clearly indicates that the emission of neutrons is due to two mechanisms, namely, the absorption of a pion by a cluster and the evaporation of neutrons from the resulting compound nucleus. In a more rigorous description, one would also have to take into account the internal nuclear cascade which develops as a result of the interaction between the fast primary nucleon and the nucleus. When we consider the evaporation of neutrons from the compound nucleus, we must remember that, if the development of the nuclear cascade occurs in a time of the order of 10^{-22} sec, the excited compound nucleus formed at the end of this process is in statistical equilibrium and will live for a much longer period of time. When the yield of the individual isotopes is measured, one can say that the pion capture process is followed with a definite probability by the emission of a particular number of neutrons (this is the "multiplicity") but, naturally, nothing can be said about the course of this process. However, if we have some definite picture of the mechanism of neutron emission and if we use some particular model to describe the process, then radiochemical methods are also very useful.

Table I shows experimental data on the mean number of neutrons emitted during the capture of negative pions by different nuclei. These data were obtained by different nuclei. These data were obtained by different meth-

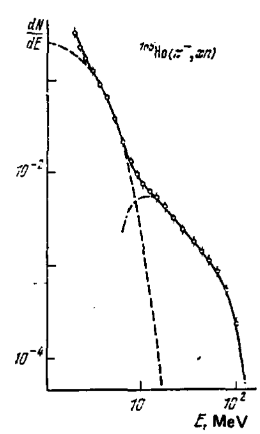

FIG. 1. Energy spectrum of neutrons accompanying pion capture by holmium nuclei.[13]

TABLE I. Mean Number of Neutrons Emitted by Nuclei During Negative Pion Capture.

Reference	C	Al	Cu	Zn	Br	Cd	Sn	I	Pb	U
Tongiorgi and Edwards (1952)[14]	1.6±0.2	2.0±0.2	—	—	—	—	6.1±0.4	—	9.3±0.4	—
Sugihara and Libby (1952)[15]	—	—	—	—	6	—	—	—	—	—
Turkevich and Fung (1953)[16]	—	—	—	2–3	—	—	—	—	—	—
Winsberg (1954)[17]	—	—	—	—	—	—	—	6,2	—	—
Russel (1956)[18]	—	—	—	—	—	—	—	—	—	12±2
Anderson *et al.* (1964)[10]	2.8±0.3	3.2±0.3	—	—	—	3.6±0.4	—	—	3.5±0.4	5.0±0.5 (7)
Venuti *et al.* (1964)[11]	—	—	7.4±0.4	—	—	—	8.5±0.5	—	9.4±0.5	—

ods, including both direct detection of pulses due to neutrons in different detectors and radiochemical identification of reaction products.

All existing data on neutron emission suggests that this process has the following characteristic features:

a) the mean number of neutrons increases from 2 to 10 as the atomic number increases from 6 to 92 (Table I);

b) there are relatively large fluctuations in the number of emitted neutrons;

c) the neutron spectrum contains two components corresponding to direct pion absorption by the cluster and to evaporation of neutrons.

Further inspection of Table I will show that the values of the multiplicity exhibit a considerable spread in some cases. This is connected with deficiencies in the experimental methods employed. However, the advent of meson factories in recent years has meant that the pion absorption process can be investigated at higher pion-beam intensities, using improved experimental techniques.

The high intensity pion beam from the synchrocyclotron at the Joint Institute for Nuclear Research in Dubna, which was designed for medico-biological research, can be used to investigate the production of different isotopes when stable isotopes are exposed to negative-ion beams. Figure 2 shows the results of such measurements in the case of lead isotopes.[19] The yield of the thallium isotopes is given in relative units. As can be seen, pion capture is accompanied by the formation of isotopes over a broad range of masses. However, it is only in the case of the ^{208}Pb target that a definite number of emitted neutrons can be assigned to each isotope. It is clear that thallium isotopes with mass numbers between 195 and 202 are produced, and this corresponds to 13 and 6 emitted neutrons, respectively.

Il'inov *et al.*[20] have carried out calculations on the neutron emission process on the assumption that the primary pion absorption event occurs either on a quasi-deuteron or an α-particle cluster. According to these calculations, the compound nucleus produced after pion absorption is excited to higher energies in the case of absorption by an α-particle cluster. This means that in this case a larger number of neutrons is evaporated and lighter isotopes are formed at the end of the process. Studies of the yield of the pion-nucleus interaction products enable one to establish the relationship between the processes involving pion absorption by the quasi-deuteron and the α-particle clusters.

Figure 3 shows both the experimental data on thallium isotope yields and the calculations of Il'inov *et al.*,[20] carried out on the assumption that 25% of all the interactions occur on α clusters and 75% on the quasi-deuterons. As can be seen, reasonable agreement between experiment and calculations has been achieved.

3. EXCITATION OF HIGH-SPIN STATES

Experiments on the production of thallium isotopes after negative pion capture by lead nuclei have shown that isomeric states with spins of $7\hbar$ are excited with appreciable probability in isotopes of mass 196 and 198.

The probability of formation of the isomer is usually normalized to the probability of formation of the nucleus in the ground state, and the quantity obtained in this way is usually referred to as the isomeric ratio.

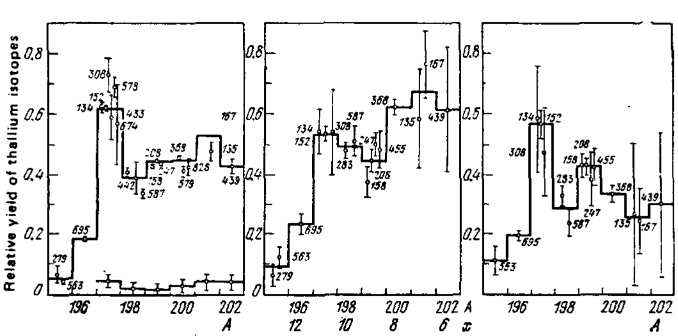

FIG. 2. Relative yield of thallium isotopes following pion capture by lead nuclei.[19]

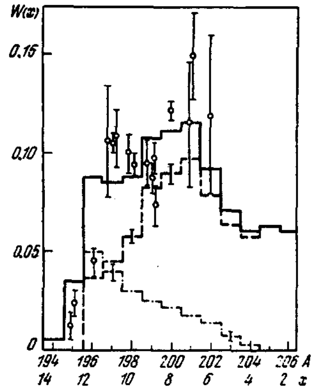

FIG. 3. Neutron multiplicity in the ^{208}Pb(π^-, xn)$^{208-x}$Tl reaction. Dashed line—calculations based on the quasideuteron absorption mechanism, dot-dash line—α-particle mechanism, solid line—obtained on the assumption that 25% of all events involve pion absorption by an α-cluster and 75% by a quasideuteron. Level density parameter $a = 0.1$ MeV^{-1} (figure taken from paper by Il'inov *et al.*[20]).

As a rule, it is a measure of the efficiency with which the isomer is produced. It turns out that this ratio attains values of up to 5.0 in the case of the thallium isotopes.[7] Experiments on the excitation of isomers were subsequently extended to other targets, and it was found that isomers were efficiently excited in the region of deformed nuclei as well. Table II shows a listing of targets for which excitation of metastable states has been observed, together with the spins of the isomers and, whenever possible, the isomeric ratios.

The highest spin among the nuclei examined so far is found in the 177 hafnium isomer.[7] Its value is $37\hbar/2$. As can be seen, in this case, the spin approaches the limiting value corresponding to the maximum angular impulse communicated to the nucleus by the emission of a high-energy nucleon from the nuclear surface.

The theory of excitation of rotational motion during negative pion capture by nuclei has been developed by Il'inov *et al.*[20] This theory is based on the angular impulse mechanism discussed in the Introduction.

Let us examine these ideas in greater detail. First, consider Fig. 4, which shows the density of nuclear

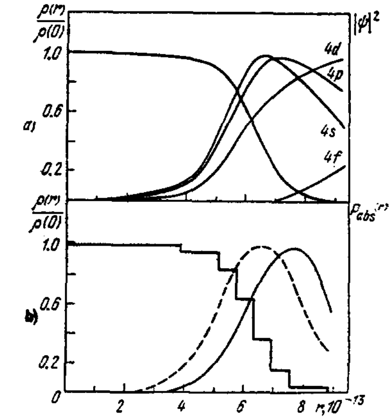

FIG. 4. a) Density of nuclear matter and pion density in the $n = 4$ state; b) density of nuclear matter calculated from the formula

$$\rho(r) = \rho_0\left[1 + \exp\left(\frac{r - c}{a}\right)\right]^{-1},$$

and the absorption probability

$$P_{abs} \sim \exp\left\{-\frac{[r - (c + \Delta r)]^2}{2\sigma^2}\right\}$$

for two different values of Δr.

matter in ^{208}Pb and the distribution of the density of pions which are in the $n = 4$ state at the time of absorption.

It is clear that the two distributions overlap appreciably only near the nuclear surface. Accordingly, as calculations show, most of the pion absorption occurs at a distance of 6–8 f from the nuclear center. The absorption of any particular particle by the nucleus leads to rotation of the latter with the nuclear spin being determined by the impact parameter.

Rotational motion of the nucleus will also occur in the case of development of an internal nuclear cascade. The angular momentum M of the final nucleus then depends on the angular momentum carried off by the cascade particles:

$$\mathbf{M} = \sum \mathbf{m},$$

where m is the angular momentum removed by a cascade particle.

TABLE II.

Reaction	High-spin isomers
Bi (π^-, xn)	^{204}mPb (9^-), ^{203}mPb ($13/2^+$), ^{202}mPb (9^-), ^{201}mPb ($13/2^+$), ^{199}mPb ($13/2^+$), ^{197}mPb ($13/2^+$)
Bi (π^-, pxn)	^{198}mTl (7^+), ^{196}mTl (7^+)
Pb (π^-, xn)	
Pb (π^-, pxn)	^{199}mHg ($13/2^+$), ^{19} mHg ($13/2^+$), ^{195}mHg ($13/2^+$), ^{193}mHg ($13/2^+$)
Tl (π^-, xn)	
Tl (π^-, pxn)	^{200}mAu (12^-), ^{198}mAu (12^-), ^{196}mAu (12^-)
Hg (π^-, xn)	
Hg (π^-, pxn)	^{197}mPt ($13/2^+$), ^{195}mPt ($13/2^+$), ^{193}mPt ($13-2^+$)
Au (π^-, xn)	
Au (π^-, pxn)	^{190}mIr (11^-)
Pt (π^-, xn)	
Ta (π^-, xn)	^{177}mHf ($37/2^-$)
Er (π^-, xn)	^{158}mHo (9^+)
I (π^-, pxn)	^{122}mSb (8^-), ^{120}mSb (8^-), ^{118}mSb (8^-), ^{116}mSb (8^-)
Sb (π^-, pxn)	^{118}mIn (4.5^+), ^{116}mIn (5^+), ^{114}mIn (5^+), ^{112}mIn (4.5^+)
Sn (π^-, xn)	^{110}mIn (7^+), ^{108}mIn (5.6^+)

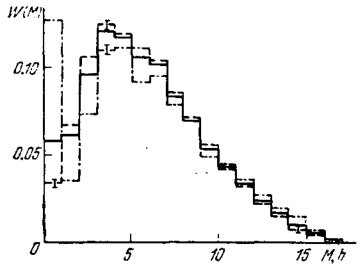

FIG. 5. Spin distribution of residual nuclei[20] (designation the same as in Fig. 3).

Figure 5 shows the distribution of the residual nuclei over the spin values on the assumption that no important changes in the nuclear spin occur during the evaporation of particles from the compound nucleus. It is clear that the nuclear spin can increase up to $15\hbar$ during the cascade process, and this is in qualitative agreement with the experimental data.

Figure 6 shows that the mean angular momentum of the residual nucleus depends on the number of emitted neutrons. The solid curve refers to the quasideuteron mechanism and the broken curve to the α-particle absorption. It is clear from the graph that the maximum spin of the residual nucleus corresponds to 6–8 emitted neutrons. According to the calculations of Locher and Myhrer,[21] nuclear rotation occurs when one fast particle leaves the nucleus and the remaining compound nucleus evaporates a few neutrons.

This can be readily understood. It reflects the connection between the development of the internal nuclear cascade and the excitation energy of the residual nucleus. Thus, if all the cascade particles are absorbed by the nucleus, the latter does not experience an angular impulse. At the same time the nucleus is found in a state with high excitation energy. Further decay of the nucleus is then accompanied by the emission of a large number of neutrons, but the nucleus continues to have a low spin value.

Likewise, when in the case of the quasideuteron mechanism, two fast particles are produced which leave the nucleus so that it remains cold, the spin of the residual nucleus can again be relatively low.

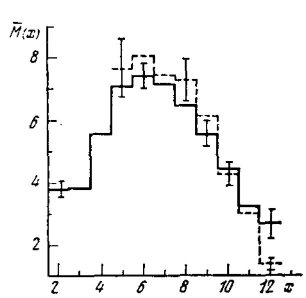

FIG. 6. Mean angular momentum of residual nucleus (in units of $\hbar$) as a function of the number of emitted neutrons. Solid line-quasideuteron absorption, broken line—α-particle absorption.

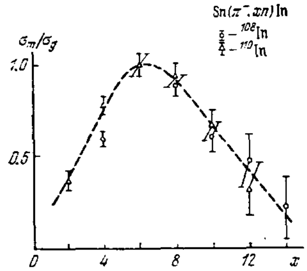

FIG. 7. Dependence of the isomeric ratio in the $Sn(\pi^-,xn)^{108,110}$In reaction on neutron multiplicity. Normalized to the case $x = 6$.

Figure 7 illustrates the results of the Dubna experiments[22] which have shown that the probability of excitation of the indium isomers does, in fact, depend on the number of emitted neutrons, roughly in the way predicted by the theory. Separated tin isotopes were used in these experiments and, by varying the targets but observing the yield of a particular isomer, it was possible to establish the isomeric ratio as a function of the number of emitted neutrons. The result of this work is that it can now be concluded that the experimental results are in reasonably good qualitative agreement with the theoretical concepts concerning the mechanism whereby rotational motion is communicated to nuclei during pion capture.

So far, we have been concerned with excitation of nuclei following emission of neutrons. Experiments have, in fact, shown that rotation can also be efficiently produced when protons as well as neutrons are emitted.

Table II shows the isomers excited in reactions with negative pions, accompanied by the emission of charged particles. The appearance of nuclear rotations in this case can also be understood in terms of the cluster mechanism of pion absorption.

Thus, if capture occurs not on the *np* cluster but on the *pp* cluster, a proton and a neutron will be produced. As in the case of the *np* cluster, the energy released is shared equally so that the proton may acquire an energy high enough to leave the nucleus, giving the latter a considerable angular impulse.

Experiments performed so far have resulted in the discovery of several tens of isomers, and this suggests that the phenomenon is quite general.

4. EFFECT OF CHEMICAL BONDING ON THE PROBABILITY OF ATOMIC AND NUCLEAR PION CAPTURE

Experimental studies by Prokoshkin and Petrukhin *et al.*,[23] performed over many years using the synchrocyclotron at the Laboratory for Nuclear Problems at the Joint Institute for Nuclear Research, have shown that negative pions can be used to investigate the structure of hydrogen-containing compounds.

The method widely used at present is based on the fact that, when a compound contains hydrogen, the process

$$\pi^- + p \rightarrow \pi^0 + n$$

is suppressed, and the degree to which it is suppressed depends on the density of the electron cloud near the proton.

Studies of the extensive class of hydrogen-containing compounds are undoubtedly important but, from the point of view of elucidating the general features of pion chemistry, it is desirable to extend the number of compounds under investigation and to include compounds that do not contain hydrogen. There is very little experimental information on the relative probabilities of formation of π-mesic atoms in chemical compounds of heavy elements.

The presence of the strong pion-nuclear interaction prevents both decays of negative pions from mesic-atom orbits and electromagnetic transitions between low-lying states of π-mesic atoms. Therefore to investigate the effect of chemical bonds on the probability of formation of mesic atoms, we measured only the relative intensities of the x rays emitted as a result of pion transitions between high-lying levels.[24-26]

The iodides of alkali metals have been investigated by Butsev *et al.*[27] Induced activity was used as the identification method. This is suitable for mesochemistry because the atomic and nuclear pion-capture probabilities are equal. In the compounds LiI, NaI, KI, RbI, and CsI which were investigated, ionic bonds are almost identical, so that the effect of only the nuclear charge on the probability of formation of mesic atoms could be investigated.

The influence of the alkali metal atoms on the yield of a given product of absorption of pions by iodine nuclei was investigated under identical conditions of irradiation and measurement. The relative yield of the high-spin isomer $^{116m}Sb(8-)$, produced with high efficiency in the $^{127}I(\pi^-, 1p10n)$ reaction, was determined.

The relative probabilities of formation of π-mesic atoms of iodine in these targets, corrected for the slowing down of the pions, were determined (Fig. 8).

It was found that the so-called Z-law of Fermi and Teller was satisfied for this type of compound. This law states that the probability of formation of mesic atoms in chemical compounds is proportional to the nuclear charge.[28]

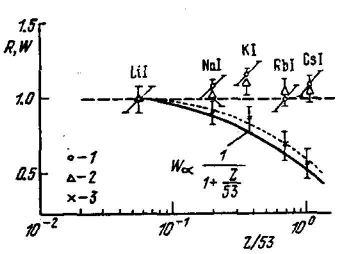

FIG. 8. Formation of the π-mesic atom of iodine as a function of the atomic number Z of the alkali metal bonded to it.[27] 1, 2—experimental ratios of γ-ray photopeaks due to the products of nuclear absorption of pions in iodine and in a monitoring material; 3—probability of formation of the πI atom. Solid line—Fermi-Teller Z—law. All numbers normalized to LiI.

5. SINGLE-NUCLEON ABSORPTION OF PIONS

The single-nucleon mechanism of pion absorption by nuclei, i.e., the reaction

$$\pi^- + p \to n,$$

is highly suppressed compared with absorption by nucleon associations.

However, Troitskiĭ *et al.*[29] have shown that, when a pion condensate is present in the nucleus, the theory developed by Migdal[30] suggests that the probability of absorption of a pion by a single nucleon is higher by a factor of 100–1000. These authors are of the opinion that measurement of the probability of single-nucleon absorption may be a critical experiment in deciding whether pion condensates are present in nuclei.

Recently, Butsev and Chultem[31] have carried out an experiment designed to detect the single-nucleon capture of a negative pion, i.e., the (π^-, n) reaction, and, hence, to demonstrate the presence of the pion condensate.

A search was made for the high-spin isomer ^{180m}Hf with a spin of $8\hbar$ which could be produced in the $^{181}Ta(\pi^-, n)$ reaction. One of the important assumptions used in Ref. 31 was that single-nucleon capture occurs on the surface of the nucleus, just as in the case of absorption by associations.

If this is so, one would expect single-nucleon capture to be accompanied, again with high probability, by the appearance of a high-spin isomer. The choice of a high-spin isomer as the final product should ensure that the background due to radiative pion capture followed by the emission of a single neutron will be suppressed.

The excitation of high-spin states during radiative capture of a pion can hardly be expected to proceed with appreciable probability.

The probability of formation of the high-spin isomer ^{180m}Hf per pion capture was estimated by Butsev and Chultem on the basis of their experiments as being less than 10^{-5}. This is not inconsistent with the analysis[13]

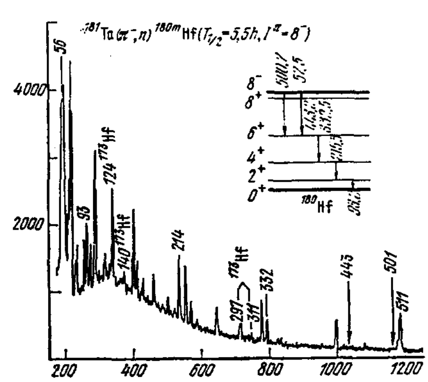

FIG. 9. γ-ray spectrum due to the radioactive nuclei produced as a result of negative-pion activation of thallium. Arrows show the position of the 443-keV and 501-keV lines of ^{180m}Hf, used to determine the probability of single-nucleon capture of pions.

of the high-energy part of the neutron spectrum in which the single-nucleon capture peak was not observed. If, in fact, there is an unambiguous relationship between single-nucleon pion absorption and the pion condensate,[29] this result may serve as an indication that this type of condensate is not present in the nucleus. At the same time, the experiment indicates once again that the quasideuteron[32] and the α-particle[33] mechanisms of absorption of stopped pions by nuclei play a dominant role.

Of course, the conclusion concerning the absence of a pion condensate drawn by Butsev and Chultem[31] can only be accepted with certain reservations. We do not in fact know the excitation spectrum of the residual nucleus after the escape of the neutron, i.e., the probability of additional escape of neutrons from the excited ^{180}Hf nucleus.

6. FUTURE WORK

We have already noted that there is a comparative shortage of experimentally established facts supporting the cluster mechanism of absorption of slow negative pions.

The excitation of rotational motion of nuclei can now be regarded as a further confirmation of this mechanism.

The most important piece of evidence appears to be the fact that the probability of excitation of isomers is found to depend on the number of neutrons emitted after pion absorption.

In our view, further confirmation of the validity of this conclusion is desirable. For example, it would be interesting to establish the angular correlation between the direction of emission of a nucleon (proton or neutron) of sufficiently high energy during the pion capture process, and the gamma rays emitted during the final stage of decay of the compound nucleus.

By recording nucleons with energies close to 100 MeV, we isolate the plane containing the angular momenta of the nucleus. By measuring the angular distribution of the gamma rays relative to this plane, we can establish whether we are, in fact, dealing with a set of angular momenta confined to the plane perpendicular to the direction of escape of the fast particle, and thus verify the validity of the hypothesis on the mechanism of excitation of rotational motion of nuclei.

In general, if we accept the cluster mechanism for pion absorption, we can go further and try to establish more accurately the contribution of the α-particle clusters. The calculations of Il'inov *et al.*,[20] which we have already mentioned, indicate that, in order to establish the contribution of the α-particle clusters, it will be very important to carry out a detailed investigation of the isotope yield for a large number of emitted neutrons. This is a relatively complicated problem because these isotopes have small yields and, as a rule, short lifetimes. However, such experiments are now possible as a result of the availability of modern techniques (on-line mass separators and fast chemical methods). Generally speaking, capture of pions by nuclei is not the only process involving the cluster structure of nuclei.

The quasideuteron mechanism of absorption of particles by nuclei may also be manifested in various processes such as, for example, photonuclear reactions, and excitation of high-spin isomers may also take place in these cases. In other words, by investigating the yield of high-spin isomers in photonuclear reactions, it may be possible to estimate the contribution of, say, the quasideuteron absorption of gamma rays.

In connection with photonuclear reactions, it is useful to note the photoproduction of pions in bound states, i.e., in orbits of the corresponding π-mesic atoms. If this process occurs, it will again be accompanied by the appearance of high-spin isomers, following the absorption of the pion from the mesic-atom orbit.

Finally, it would be interesting to investigate the excitation of high-spin nuclear states following the capture of slow negative kaons because, here again, the process occurs near the nuclear surface.

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