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ISOMER EXCITATION AND DEPLETION IN NUCLEAR REACTIONS

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I. Introduction

Radioactive beam facilities which are being rapidly developed nowadays apart from possessing many promising properties open up a new possibility for creating a technique of isomeric beams for nuclear structure and reaction studies. In literature one can find the reports on production of secondary isomeric beams in the fragmentation-like reactions [1-7] and a subsequent accumulation of isomeric nuclei in the storage ring [8] as well as their consumption for nuclear interaction studies [9]. High purity of the isomeric beam is the most important quality parameter, thus, isomer-to-ground state ratios should be studied systematically in a variety of reactions. The cited articles can be considered a promising indication of the future success in the experiments with the isomeric beams. However, it is clear that the realization of these possibilities requires much more effort in the extensive investigation and optimization of the production reactions, methods of isomer-ground state separation and purified isomeric beam acceleration.

Many different schemes of production of radioactive and isomeric beams are being considered today: starting from a direct consumption of the reaction products isolated by the fragment separation technique and ending with a high-resolution separator for low-energy radioactive ions with their subsequent acceleration to the required energy in the post-accelerator. Also, possibilities for the beam selection in the resonant accelerator or in the storage ring used as a precision mass-separator are being realized. It is difficult to judge now what method is most efficient and the answer possibly depends on the nuclide species and the energy required by the experimentalists.

In this talk the problem of isomeric nuclei as participants of nuclear reactions is discussed in some specific aspects.

II. Isomers are exotic “in structure” nuclei

A large number of isomeric states can be found through the nuclide chart, especially if one takes into consideration the short-lived states down to $T_{1/2} \approx 0.1$ μs. An emphasis will be put on the relatively long-lived isomers, with $T_{1/2} \geq 0.1$ s, since such a lifetime allows an isomeric beam production using even slow systems with the ion source. The list of such isomers in the $A \leq 90$ region is presented in Table 1 and the relative mass difference values, $\Delta M/M$ are given there:

$$\Delta M = M_i - M_g. \qquad (1)$$

High-spin isomers in heavier nuclei are displayed in Fig. 1 in accordance with their mass number. It is clear that in heavy nuclei the high-spin states (J of up to $18\hbar$) can manifest themselves as long-lived isomers. Unlike that the highest values of the $\Delta M/M$ parameter are realized in the case of light and medium-mass nuclei.

Among a variety of isomers one can select individual nuclides which are most exotic in some properties. They should be considered the first candidates for the experimental studies. In our opinion the attention can be concentrated on the following isomers:

1. $^{52}Fe^m$, $^{53}Fe^m$ and $^{53}Co^m$ isomers have an outstanding excitation energy, so the $\Delta M/M$ values of as high as $\approx 10^{-4}$ are reached. This property reflects, perhaps,

Table 1. Properties of the isomeric states in nuclides with A≤90

Nuclide	$T_{1/2}$	J^π	ΔM/M, 10^{-5}	Nuclide	$T_{1/2}$	J^π	ΔM/M, 10^{-5}
^{24}Na	20 ms	1^+	2.11	^{81}Se	57.3 m	$7/2^+$	0.14
^{24}Al	0.13 s	1^+	1.96	^{83}Se	70 s	$1/2^-$	0.30
^{26}Al	6.36 s	0^+	0.94	^{74}Br	46 m	4^+	0.020
^{34}Cl	32 m	3^+	0.46	^{77}Br	4.3 m	$9/2^+$	0.15
^{38}Cl	0.72 s	5^-	1.90	^{79}Br	4.9 s	$9/2^+$	0.28
^{38}K	0.93 s	0^+	0.37	^{80}Br	4.42 h	5^-	0.12
^{42}Sc	62 s	7^+	1.58	^{82}Br	6.1 m	2^-	0.060
^{44}Sc	2.44 d	6^+	0.66	^{84}Br	6.0 m	6^-	0.38
^{45}Sc	0.32 s	$3/2^+$	0.029	^{79}Kr	50 s	$7/2^+$	0.18
^{46}Sc	18.7 s	1^-	0.33	^{81}Kr	13 s	$1/2^-$	0.25
^{50}Sc	0.35 s	2^+	0.55	^{83}Kr	1.83 h	$1/2^-$	0.054
^{50}Mn	1.74 m	5^+	0.49	^{85}Kr	4.48 h	$1/2^-$	0.39
^{52}Mn	21 m	2^+	0.78	^{78}Rb	5.74 m	4^-	0.14
^{58}Mn	3.0 s	0^+	-	^{81}Rb	30 m	$9/2^+$	0.11
^{60}Mn	1.8 s	3^+	0.48	^{82}Rb	6.4 h	5^-	0.13
^{52}Fe	46 s	12^+	14.1	^{84}Rb	20.3 m	6^-	0.59
^{53}Fe	2.58 m	$19/2^-$	6.16	^{86}Rb	1.02 m	6^-	0.69
^{53}Co	0.25 s	$19/2^-$	6.46	^{90}Rb	4.3 m	3^-	0.13
^{54}Co	1.48 m	7^+	0.40	^{83}Sr	5.0 s	$1/2^-$	0.33
^{58}Co	9.2 h	5^+	0.046	^{85}Sr	68 m	$1/2^-$	0.30
^{60}Co	10.5 m	2^+	0.10	^{87}Sr	2.8 h	$1/2^-$	0.48
^{62}Co	13.9 m	5^+	0.038	^{83}Y	2.85 m	$3/2^-$	0.080
^{68}Cu	3.8 m	6^-	1.14	^{84}Y	40 m	5^-	0.64
^{70}Cu	47 s	4^-	0.21	^{85}Y	4.9 h	$9/2^+$	0.025
^{69}Zn	13.9 h	$9/2^+$	0.68	^{86}Y	48 m	8^+	0.27
^{71}Zn	3.96 h	$9/2^+$	0.24	^{87}Y	13.4 h	$9/2^+$	0.47
^{73}Zn	5.8 s	$7/2^+$	0.29	^{89}Y	16.1 s	$9/2^+$	1.1
^{74}Ga	9.5 s	0	0.087	^{90}Y	3.19 h	7^+	0.81
^{73}Ge	0.5 s	$1/2^-$	0.098	^{85}Zr	10.9 s	$1/2^-$	0.37
^{75}Ge	48 s	$7/2^+$	0.20	^{87}Zr	14 s	$1/2^-$	0.42
^{77}Ge	53 s	$1/2^-$	0.22	^{89}Zr	4.18 m	$1/2^-$	0.71
^{79}Ge	39 s	$7/2^+$	0.25	^{90}Zr	0.8 s	5^-	2.77
^{81}Ge	7.6 s	$1/2^+$	0.90	^{87}Nb	3.7 m	$1/2^-$	-
^{69}Se	1.8 m	-	-	^{88}Nb	7.8 m	4^-	-
^{73}Se	40 m	$3/2^-$	0.038	^{89}Nb	1.18 h	$1/2^-$	-
^{77}Se	17.4 s	$7/2^+$	0.23	^{90}Nb	18.8 s	4^-	0.15
^{79}Se	3.9 m	$1/2^-$	0.13	^{90}Tc	49 s	5	0.60

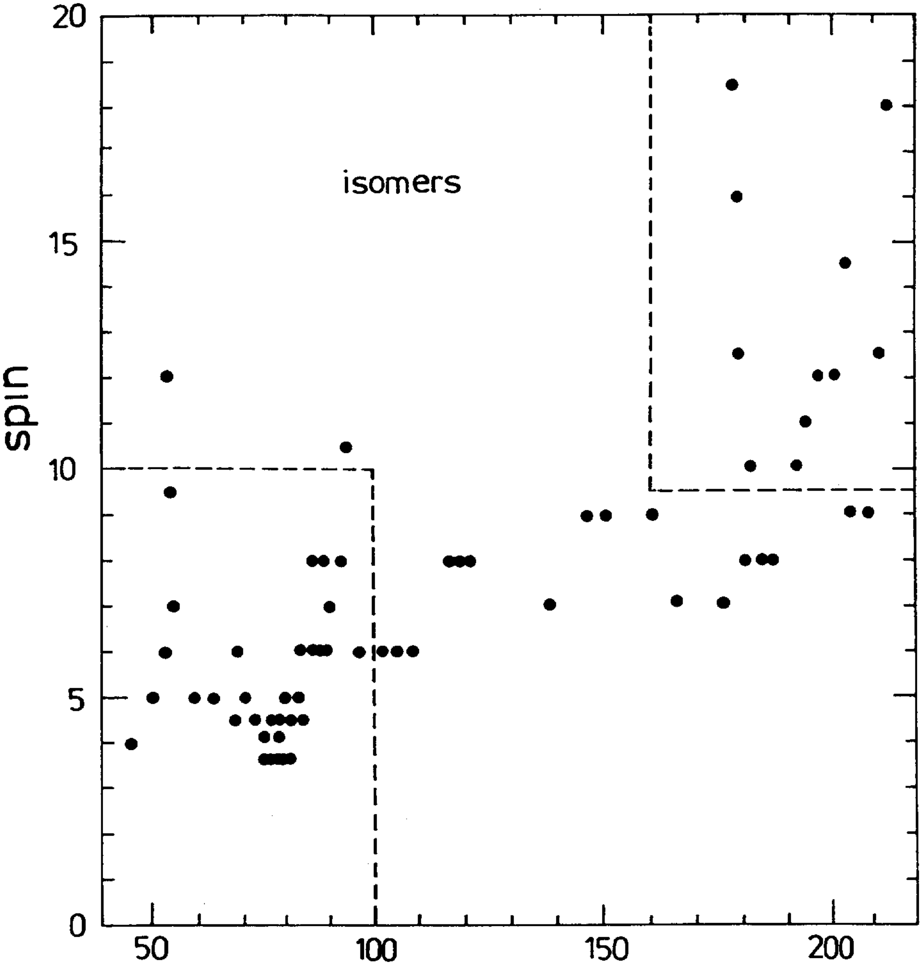

Fig. 1. Isomeric state spins versus mass numbers.

their exotic structure and, in addition, it makes them the best candidates for the isomer-ground state separation in resonant systems and in magnetic analyzers.

2. ^{177}Hf^{m_2}, ^{178}Hf^{m_2} and ^{212}Po^{m} isomers being of exotic five- and four-quasiparticle configurations can be selected as the species with the highest spin of up to 37/2 $\hbar$.
3. The exotic structure of spontaneously fissioning isomers, such as ^{242}Am^{m}, $T_{1/2}$=14 ms, has been the subject of wide discussion. One can also add the isomers of the Sb region nuclei (for instance ^{116}Sb^{m}, $T_{1/2}$=60.3 min, $J^{\pi}=8^{-}$) because they are formed as a result of the intruder level manifestation. The role of the deformation change is important both in the region of Am and Sb isomers.

The presented choice is in principle more or less arbitrary. One can use other criteria and select other isomers, for instance, the states which are valid from the point of view of the astrophysical aspect or the ones which are promising for the gamma-ray laser pumping. Here we made a selection basing only on their nuclear properties.

III. Isomer-to-ground state ratios in reactions

High-spin isomeric states are populated in reactions after the particle emission via electromagnetic transition cascades. In the statistical model their yield depends on the initial angular momentum distribution and on the level density parameters of the reaction product. Thus, in the statistical approach it is very natural to establish an isomer-to-ground state ratio dependence on the spin deficit, ΔJ, in the reaction:

$$\Delta J = J_t + J_b + \ell_m - J_i, \qquad (2)$$

where J_t, J_b and J_i are the spin values for the target, projectile and isomeric product nuclei, ℓ_m is the maximum angular momentum released in the reaction. The isomer-to-ground state ratios have been measured in many cases. As an example the excitation functions and σ_m/σ_g values are shown in Fig. 2 for ^{177}Lu^{m}, ^{178}Hf^{m_2} and ^{179}Hf^{m_2} isomers as measured in [10] in the reaction ^{4}He + ^{176}Yb.

The systematic dependence of the σ_m/σ_g values versus ΔJ was plotted for the isomers of rare-earth deformed nuclei. It is shown in Fig. 3a, b and c, respectively, for the reactions induced by thermal neutrons, bremsstrahlung photons and α-particles. The literature data were attracted as well as our measurement results, for references and details see [10]. One can observe an exponential growth of the σ_m/σ_g values when the spin deficit is decreasing and then going to the spin excess. It is understandable since more probable gamma-ray cascades are opened for the isomeric state feeding when the spin is high enough. The slope of the dependencies at the a, b and c diagrammes is not the same. It is due to different spin distribution widths in the reactions induced by different projectiles.

From the regular behaviour of the σ_m/σ_g values shown in Fig. 3 one can predict that in the heavy-ion induced reactions the isomer-to-ground state ratios should be as a rule at a level of 1.0. This is because the mean angular momentum of the reaction product exceeds the isomer spin in the majority of cases. As one can see in Table 2, taken from ref.[7], this prediction is really confirmed by the experimental results on the isomers production in the ^{112}Sn + Ni reaction at 63 MeV/u Sn-ion energy. Many isomers have the yield at a level of 50% of the

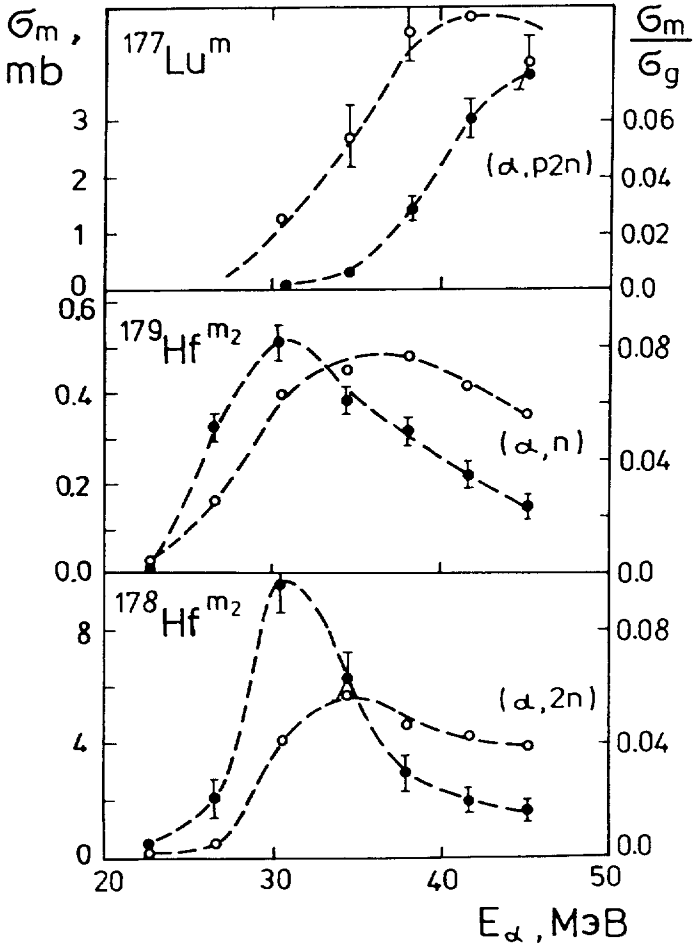

Fig. 2. Excitation functions (•) and isomer-to-ground state ratios (o) for the ^{177}Lu, ^{178}Hf and ^{179}Hf isomers produced in the ^{4}He + ^{176}Yb reaction [10]. Dashed line is a guide over experimental points.

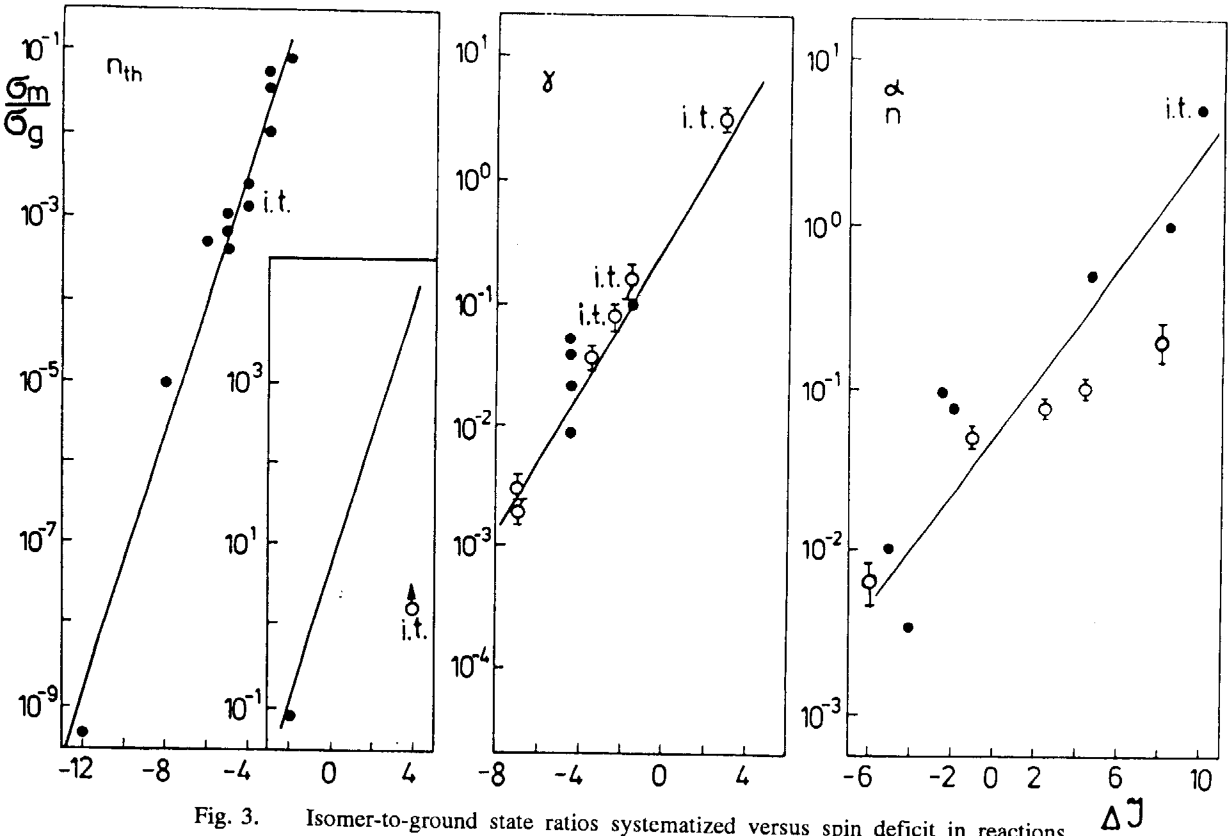

Fig. 3. Isomer-to-ground state ratios systematized versus spin deficit in reactions induced by thermal neutrons (a), photons (b) and α-particles (c). The "i.t." index indicates high-spin targets.

total nuclide yield. It is worthwhile to point out that the purity of the $^{42}Sc^m$ isomeric beam as high as 98% was detected [2] for the products of the ^{40}Ca + ^{12}C reaction at 30 MeV/u. An extremely high relative yield of the isomer can be explained obviously by the unique coupling between the reaction mechanism and the isomer structure in this case.

The total production yields of isomeric beams at the fragment-separators do not exceed the value of 10^{-9} per projectile ion. It means that reactions with intensive light particle beams could be preferable for reaching the highest absolute production rate. Thus, the production rate optimization contradicts the beam purity requirement because the isomer-to-ground state ratio is rather low for light projectiles. So, the problem of the isomer-ground state separation becomes important. In addition to traditional methods of hot source chemistry and magnetic or resonant analyzers one has to consider new possibilities of laser technique which has made an impressive progress during the past years, see for instance ref.[11]. It can meet the requirements of high efficiency and rapidity of separation.

IV. Reactions with isomeric nuclei

Up to now the reactions with isomers were studied using naturally abundant $^{180}Ta^m$ (J^π=9$^-$) [12-14] and recently produced $^{178}Hf^{m_2}$ (J^π=16$^+$) [15-17] targets. The only case of the isomeric beam induced reaction was presented by the Japanese group [9], they detected the Coulomb excitation of the ^{174}Hf (J^π=8$^-$) isomer projectiles. So, the studies of reactions with isomeric nuclei lack experimental data due to methodical problems. Such a situation should stimulate intellectual efforts in order to specify important objectives and appropriate methods of the experiments with isomers. Finally, some advantageous and informative studies with individual isomers should be planned.

We would like to propose here a few experiments with isomers. However, for a better explanation of these ideas let us formally introduce some new terminology. Excitation of an isomeric state can be formally considered as an absorption of some special particle by a ground state nucleus. One can introduce a new term - “structuron”, just for the sake of convenience in discussions and explanations. The structuron has a zero electric and baryon charge, but it has a definite energy, spin and structure type. Excitation of any quasi-particle state can be described as an absorption of some special sort of structuron unlike the excitation of collective band states. An example of the simplest structuron absorption by a target nucleus is a well-known spin-flip in the nucleon scattering process.

As far as the reactions with isomers participation are concerned, one can state that the central problem is to study the probability of the isomeric structuron transfer in different processes. That includes both the isomer excitation and isomer depletion in nuclear reactions. It has been mentioned above that the isomer-to-ground state ratios were measured in many reactions used for the isomer production. However, the structuron formation mechanism is supposed normally to be connected with a multi-step decay of the excited reaction residue. Isomer depletion was also observed in some cases [12-14] and the process occurring via special intermediate K-mixed levels was discussed. Thus, one can formulate two interesting problems for the future investigations:

1. Study of isomer-to-ground state ratios in the group of direct nuclear reaction and search for some special cases when the isomeric structuron transfer is superallowed.
2. Study of the isomer depletion in the reactions with isomeric targets or projectiles and search for special high-probability cases.

Isomer depletion can be accompanied by a direct transfer of the structuron to the projectile particle. Its energy is increased due to that, thus, the "superelastic" scattering takes place. For the case of thermal neutron scattering the process of "neutron acceleration" was evaluated in ref.[18,19]. Though some experimental indications of the neutron acceleration were reported in [20], this process as well as charged particles superelastic scattering were not studied in detail due to their low probability. And, perhaps, more suitable reactions should be selected for the experiments. This point is discussed below.

V. Experiments on the $^{180}Ta^m$ and $^{212}Po^m$ depletion

A schematic sketch of the isomeric $^{212}Po^m$, $^{178}Hf^{m_2}$ and $^{180}Ta^m$ configurations is presented in Fig. 4. One can see that four nucleons with an aligned angular momentum are orbiting in the equatorial plane around the ^{208}Pb and ^{174}Yb cores and only two nucleons around the ^{178}Hf core to form the mentioned isomeric states. Let us consider now the collision of deuterons with $^{180}Ta^m$. When an external deuteron approaches the orbit of the aligned proton and neutron, it can replace the orbiting nucleons by means of ejection of a deuteron or unbound p and n from the valence orbit. Such process looks very natural and probable. Thus, the probability of the isomeric structuron ejection in the $^{180}Ta^m(d,d')$ knock-out reaction could be anomalously high. It means that in the deuteron irradiation one can detect the depletion of $^{180}Ta^m$ to $^{180}Ta^g$ with a high enough cross-section.

A similar situation is expected in the depletion of the $^{178}Hf^{m_2}$ and $^{212}Po^m$ isomers under an α-particle irradiation. The substitution of the orbiting nucleons by an external α-particle in the knock-out reaction is illustrated by Fig. 4. The real mechanism of the depletion can be more complicated than a direct substitution leading to the nucleus ground state. Perhaps, some rearrangement of the nucleon orbits takes place. Still, an enhanced probability of the process is expected when an isomeric nucleus collides with a particle identical to the quasi-particle excitation in the nucleus. The structuron exchange can take place.

Let us discuss the practical point, how to detect these processes. It is easy to measure a depletion cross-section for $^{180}Ta^m$ by γ-activity (E_γ=93.3 and 103.6 keV) of $^{180}Ta^g$, $T_{1/2}$=8.15 h and for $^{212}Po^m$ by α-activity (Q_α=8.95 MeV) of $^{212}Po^g$, $T_{1/2}$=0.3 μs. In order to deduce an enhanced cross-section one can compare the results of the deuteron and proton irradiation of a $^{180}Ta^m$ target at the same velocities (on the barrier); also a comparison of the α- and ^3He-induced reactions in the case of the $^{212}Po^m$ isomer could be informative.

A short lifetime of the $^{212}Po^g$ ground state ($T_{1/2}$=0.3 μs) permits the detection of its decay α-particles in coincidences with the reaction α-particles. In this version the background should be suppressed significantly and the process of the superelastic scattering with the isomer depletion can be discovered in a high-sensitivity experiment. In the cases of $^{180}Ta^m$ and $^{178}Hf^{m_2}$ a direct depletion to the

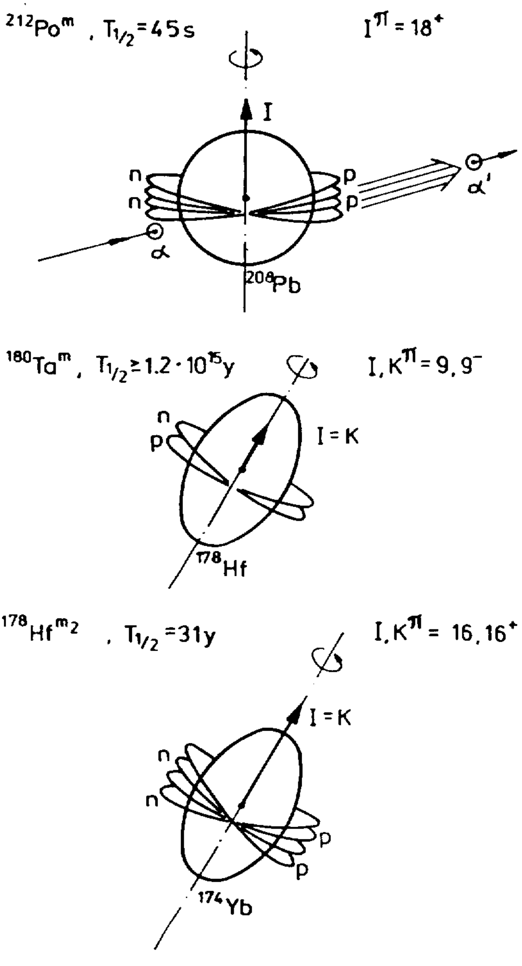

Fig. 4. Schematic sketch of the $^{178}Hf^{m_2}$, $^{180}Ta^m$ and $^{212}Po^m$ isomers configuration.

ground-state in a superelastic scattering of deuterons and alphas, respectively, can be searched for too, however, with a poorer sensitivity than in the case of ^{212}Po^{m} isomeric nuclei because of the coincident radiation absence.

A pure isomeric beam of ^{212}Po^{m} ions can be produced either by the method of fragment-separation or by the secondary acceleration of the ^{212}Po^{m} (45 s) nuclei produced in a nuclear reaction. The ground-state ^{212}Po nuclei being produced are decaying rapidly and are not present in the ^{212}Po^{m} beam. Thus, the proposed experiment can be successful.

Still, one should not exclude a possibility that the structuron exchange in all direct interactions is damped drastically due to the reaction mechanism. It takes place if the structuron formation requires a multistep rearrangement in the decay of a rather long-lived evaporation residue. Then the processes discussed above cannot be detected because of their low probability. Only experiment can solve the problem of direct excitation and depletion of isomeric states.

In general this situation is similar to the problem of high-K isomer fission proposed in ref.[21] for the ^{178}Hf^{m_2} isomer. The induced fission probability could be enhanced because the initial spin of the isomeric state leads to a wider spin distribution of a compound nucleus. And it could be decreased because four decoupled nucleons increase the fission barrier. Only the experiment can solve the problem whether the isomeric structuron promotes or inversely impedes the fission.

Both physical problems - of fission and of direct depletion of isomers, can be solved experimentally in the style of “yes” or “no” answers. It looks intriguing for the future investigations.

VI. Problem of isomer + isomer interaction

At present isomeric materials are available in quantities sufficient for production of the targets of 10–100 μg/cm^2 thickness, at least it is possible in the case of the ^{180}Ta^{m} isomer [22]. Creation of the isomeric beams allows us to dream about the isomer + isomer interaction. Such an experiment may be realized in future. Since the problem is interesting in principle, it can be studied now at least in a theoretical approach.

In the isomer + isomer interaction two nuclei and two structurons are involved. Thus, a variety of processes take place. Now we can discuss two interesting processes:

1. Addition of structurons and
2. Recombination of structurons.

As an example of the first process let us consider the following reaction:

$$^{42}\mathrm{Sc}^{m}(7^{+}) + {}^{180}\mathrm{Ta}^{m}(9^{-}) \rightarrow {}^{42}\mathrm{Sc}^{g}(0^{+}) + {}^{180}\mathrm{Ta}^{m_2}(15^{-}) - 0.73\ \mathrm{MeV}. \qquad (3)$$

A slight change in a relative motion meets the requirements of energy and spin conservation. Both the target and projectile isomers are two-quasiparticle (π,ν) states. Therefore, the structuron can be transferred from a ^{42}Sc^{m} to the ^{180}Ta^{m} nucleus with the addition of the structurons and formation of a four quasiparticle isomeric state in ^{180}Ta. It is known now from ref. [23]: J, K^{π}=15,15^{-}, $T_{1/2}$=31 μs, E^{*}=1451 keV. The properties of ^{180}Ta^{m_2} are convenient for its decay detection with a high efficiency by a 4π granular γ-spectrometer of the “Miniball” or “Euroball” type. $^{42}Sc^m$ can be one of the most intensive isomeric beams as it is clear from [2]. Thus, the reaction (3) is an advantageous case for the realization.

Another sort of reaction is the structuron recombination as a result of the rearrangement of nucleon orbits in the nucleus-nucleus collision. A prominent example of such a reaction is the following process:

$$^{52}Fe^m(12^+) + {}^{178}Hf^{m_2}(16^+) \rightarrow {}^{52}Fe^g(0^+) + {}^{178}Hf^g(0^+) + 9.3\ \text{MeV}. \qquad (4)$$

In this reaction the depletion of high-excited and high-spin isomers can happen in a nucleus-nucleus collision. And the reaction energy can be released either in the form of kinetic energy of a relative motion (superelastic scattering) or in the form of γ-cascades in both nuclei with the total multiplicity of as high as $M_\gamma \approx 15$. Both variants – superelastic scattering and high-multiplicity γ-cascades are convenient for the detection since a very specific signal cannot be created by any background process.

VII. Conclusion

Reactions with isomeric nuclei are considered. Enhanced probability of the isomer direct excitation or depletion in special reactions is discussed. The experiments for the study of this problem are proposed which could be performed when pure isomeric $^{212}Po^m$ and $^{178}Hf^{m_2}$ beams are available. The problem of the isomer+isomer interaction is touched upon for the first time.

Table 2. List of the isomers studied [7] at 63 MeV/u primary beam energy in the reaction ^{112}Sn + Ni

Nuclide	E^*, keV	J^π	$T_{1/2}$, μs	Yield, 10^{-10} per projectile	Isomer-to-total yield ratio, %
^{43}Sc	3123	$19/2^-$	0.469	$1.9 \cdot 10^{-2}$	27
^{54}Fe	6527	10^+	0.364	$2.3 \cdot 10^{-2}$	11
^{69}Se	574	$(9/2^+)$	0.853	$1.7 \cdot 10^{-3}$	42
^{71}Se	260	$(9/2^+)$	19	0.39	–
^{93}Ru	2083	$21/2^+$	2.15	0.11	35
^{96}Pd	2531	8^+	2.2	$1.0 \cdot 10^{-2}$	39

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Возбуждение и разрядка изомеров в ядерных реакциях

В связи с прогрессом в получении радиоактивных и изомерных пучков обсуждаются некоторые особенности ядерного взаимодействия изомеров. Отобраны наиболее интересные для исследований изомерные состояния. Обсуждаются величины изомерных отношений при их получении в ядерных реакциях. Возбуждение или разрядка изомерного состояния трактуются в терминах передачи специального изомерного возбуждения (структурона) при ядерном взаимодействии. Разрядка изомерных уровней ^{180}Ta^{m} и ^{212}Po^{m} может оказаться вероятным процессом в некоторых специальных реакциях замены (выбивания).

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Isomer Excitation and Depletion in Nuclear Reactions

In the light of the radioactive and isomeric beams progress the problem of nuclear interaction of isomers is discussed in some specific details. The most promising for the investigations isomers are selected. The production isomer-to-ground state ratios are discussed. The excitation and depletion of an isomeric state is described in terms of a special isomeric excitation (structuron) transfer in the nuclear interaction. The depletion of ^{180}Ta^{m} and ^{212}Po^{m} isomers in some special substitution (knock-out) reactions is presumed to be a probable process.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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