Origin of the anomalous population of long-lived isomers in odd-*A* Te isotopes

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The anomalously high activation yield of the $11/2^-$ isomeric states in odd-*A* Te isotopes in the (n,γ), (γ,n), and (γ,γ') reactions could be understood by the funneling of the initial gateway states through the lowest isolated $5/2^-$ state. The peculiar deexcitation mode is governed by favored $M1$, $E2$ transitions inside the family of negative-parity states built in accordance with IBFM calculations by a coupling of the dominant $1h_{11/2}$ and $3p$ configurations to the neighboring bosonic even-even core. [S0556-2813(99)04907-9]

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It has been known for a long time that the nuclear isomeric states can be populated by different ways. In any case the isomer population must proceed through the initial channel with a more or less broad energy and spin distribution depending on the process. The following depopulation by γ transitions has been traditionally described in terms of statistical cascades with transition probabilities which depend on the level density and the energy of a given cascade. Generally, this mechanism works well excluding some cases where the isomer populations are too large manifesting nonstatistical effects.

The very large cross section for the population of isomers in the (γ,γ') reaction through an initial channel of $\approx 2-4$ MeV has recently attracted interest [1–5]. To a large degree the interest in this topic has been motivated by research towards determining the feasibility of a γ-laser whose pumping would rely on the deexcitation of long-lived isomers.

In this context one of the interesting objects are the longest-lived isomers in odd-*A* Te isotopes. The (γ,γ') excitation functions of the isomer yield $^{123}\mathrm{Te}^m$ ($T_{1/2}=119.7$ d) and $^{125}\mathrm{Te}^m$ ($T_{1/2}=58$ d) [2] have several discrete excitation energies. This means that photoexcitation of the $11/2^-$ isomers from the target state with the spin of $1/2^+$ proceeds by resonant absorption through isolated initial states with a narrow spin bin $\leqslant 3/2$. Moreover, as was emphasized by the authors of Ref. [2], no consistent description could be obtained by assuming broad absorption through densely spaced levels. There have been few attempts to explain the structure of gateways on microscopic basis [6,7,5]. In general, the resonant absorption in each case proceeds through the admixtures of the ground state configuration while admixtures to the wave function in intermediate states permitting dipole or collective $E2$ transitions from higher phonon even-even core configurations are responsible for the branching to the isomer.

Enhanced isomer population of Te isotopes besides resonant photoabsorption has also been established after the irradiation with thermal and resonance neutrons [8,9] as well as in the (γ,n) reaction [10]. The initial state in thermal neutron capture is not related to ground state due to the accidental character of the capture state wave function. The spin of the initial state in the case of thermal neutron capture on even-even targets is $1/2^+$. For the (γ,n) reaction spin bins are restricted to values of 1/2–5/2. Initial channels for both latter reactions lie at energies about 6–7 MeV.

The anomalous high-spin isomer population in the Te region cannot be caused by any reason connected with level density or spin parameters. It has to be due to peculiarities of γ cascades at the final stage of isomer feeding. Therefore the studies of the latter could be promising for reactions with statistical behavior as well as for the understanding of gateways in the resonant photoabsorption process.

The question arises which intermediate states are contributing to the energy transfer and how far the nuclear structures are responsible for the peculiar decay mode of these states. The purpose of the present Brief Report is to propose candidates for gateways which could shed light on the mechanism of the anomalous population of the isomers. Special attention is dedicated to the identification of the important nuclear structures which could be responsible for the peculiar deexcitation mode. The investigation is based on spectroscopic studies of the radiative capture of thermal neutrons and the (d,p) reaction on doubly even Te isotopes.

Thermal neutron capture studies on ^{122,124,128}Te were performed at the light-water reactor LWR-15 at Řež using a neutron guide [11] and semiconductor detectors. Tellurium samples enriched to 88.4, 92.4, and 99.3% in ^{122}Te, ^{124}Te, and ^{128}Te, respectively, were used in single γ-ray and $\gamma\gamma$-coincidence measurements. The energy calibration was made relative to low- and high-energy transitions in ^{124}Te [12], ^{36}Cl [13] and prominent background lines of ^{2}H, ^{60}Co,

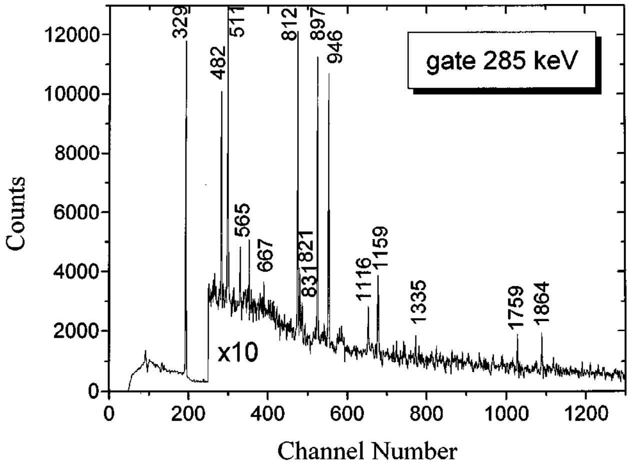

FIG. 1. The example of the background-subtracted coincidence spectra gated on the three lowest transitions terminating on the $11/2^-$ isomeric states in ^{123}Te. Peaks are marked by their energies in keV.

etc. Relative intensities were determined from special Ra and ^{35}Cl(n,γ) measurements. The $\gamma\gamma$-coincidence measurements were undertaken with two 22% HPGe and 12% Ge(Li) detectors; in the case of ^{128}Te two 22 and 28% HPGe detectors were used. Coincidence spectra were obtained off-line by setting gates on primary and secondary transitions; one of them is presented in Fig. 1.

The (d,p) measurements were performed at the Munich tandem accelerator with the high resolution Q3D magnetic spectrograph [full width at half maximum (FWHM) ≈ 5 keV]. Enriched targets of the same quality as in thermal neutron capture studies on thin carbon foils were used. Spectra in each case were measured at least up to 3 MeV excitation energy.

The level schemes have been deduced from the present complex studies in combination with the available data from the NSDF. Evidence of population in the nucleon transfer reactions or of primary feeding in thermal neutron capture reaction, or at least one deexciting transition supported by a coincidence relation were the main arguments for the inclusion of levels in the scheme. New levels were introduced if they were confirmed in three or more independent gates or sum-coincidence spectra with sufficient statistics. Spin-parity assignments and limits are derived from all available data. For levels populated by primary transitions the J^π values are assumed to be $1/2^\pm$ or $3/2^\pm$. For levels not populated by primary transitions it is assumed that no $M2$ (or higher multipolarity) transitions are observed.

Three fragments of the levels schemes relevant to the scope discussed here are shown in Fig. 2. One notes a striking similarity of the three schemes in which only branchings to the family of negative parity states connected to the isomer and the ground state are shown. A clue to the understanding of the anomalous feeding of the $11/2^-$ isomeric states in the studied Te isotopes give the newly established $5/2^-$ states at 862, 1071, and 1221 keV in nuclei with mass numbers $A=123$, 125, and 129, respectively. These funnels effectively collect "statistical rain" of γ cascades from

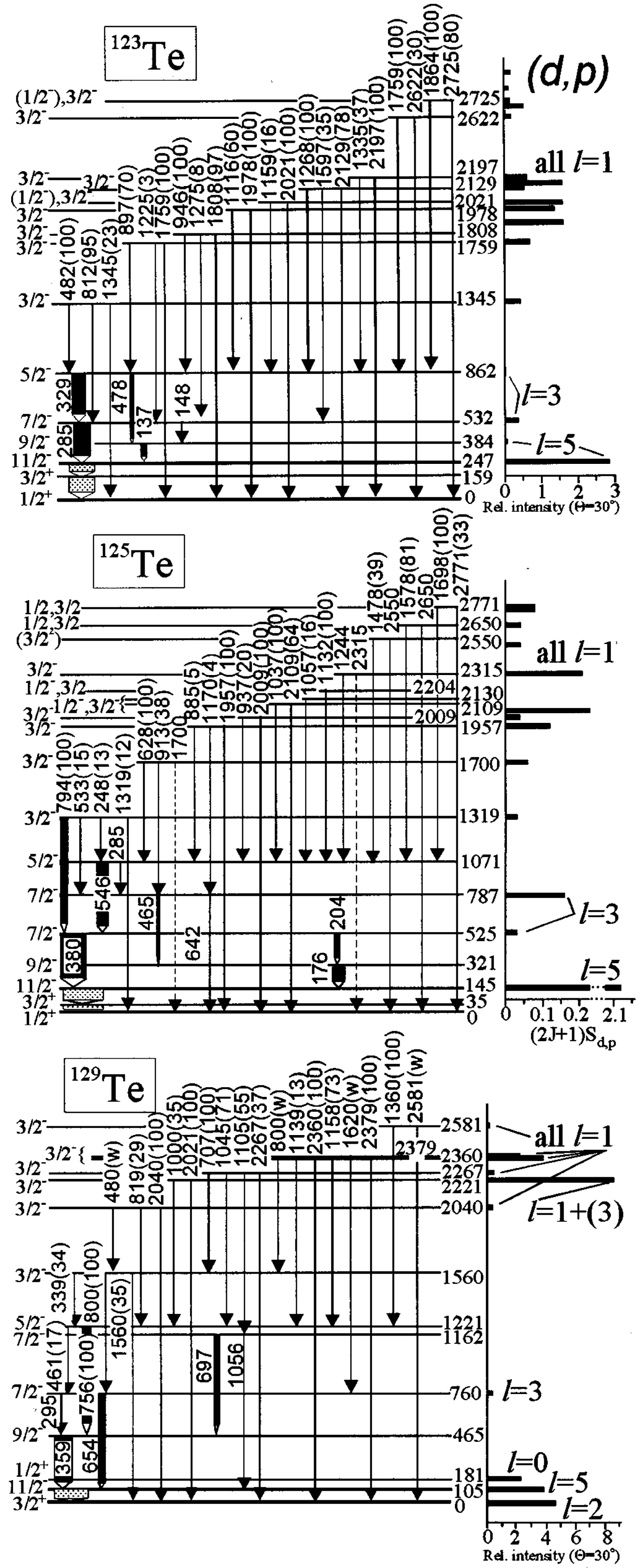

FIG. 2. Partial level schemes showing the feeding of the $11/2^-$ isomeric states in ^{123}Te (top), ^{125}Te (middle), and ^{129}Te (bottom). The linewidths of the transitions is proportional to the intensity of the γ transition. Transitions to the positive-parity states besides the ground states are not given.

many high-lying states. In the case of the ^{123,125}Te nuclei about 55% of the whole γ intensity accumulated in the isomeric $11/2^-$ goes through these $5/2^-$ states. The lowest-lying $3/2^-$ states are also important deexciting directly to the low-lying $7/2^-$ states by $E2$ transitions in each isotope. The role of the $5/2^-$ state at 1221 keV in the isomer population in ^{129}Te slightly decreases (about 43%) but the role of the neighboring partner $7/2^-$ state at 1162 keV increases (about 26%). At the same time many high-lying 3/2 and 1/2 states depicted in Fig. 2 show significant branchings to the ground state. For this reason they might be considered as unknown earlier gateways in the resonant photoabsorption process at least in a low energy region $E \leqslant 3$ MeV.

Further information on the wave function content of the observed states gives the analysis of the (d,p) data. The corresponding spectroscopic strengths are plotted on the right hand side in Fig. 2. Besides the $11/2^-$ states all other low-lying states of negative-parity $9/2^-$ and $7/2^-$ are only weakly populated in (d,p). The $5/2^-$ states are entirely absent in (d,p). There is no evidence that they were observed in any other nucleon transfer reaction in neighboring nuclei. Thus we may conclude that the structure of these states is complicated. Both expected $2f_{7/2}$ and $2f_{5/2}$ single particle components are of minor importance. The next group of negative-parity states is populated by $l=1$ transitions which are spread over an excitation energy of 2–3 MeV indicating wide fragmentation of the $3p_{3/2}$ and $3p_{1/2}$ single-particle strengths.

As an attempt to reach a more detailed understanding of the structures of negative-parity states we performed IBFM-1 calculations with the even-even (Te) cores and the boson-fermion interaction strength parameters close to those used for the isotonic Xe and Ba [14,15]. Quasiparticle energies and shell occupancies have been calculated with a standard BCS procedure starting from the 50-82 shell single-particle levels provided by Ref. [16]. Besides level energies, $M1$ and $E2$ transitions have been also calculated, with effective boson charge and g factor chosen such as to describe the $B(E2;2_1^+\rightarrow 0_1^+)$ value and the magnetic moment of the 2_1^+ state from the core ^{124}Te; fermion charge and g factors were chosen according to the prescriptions used in Refs. [14,15]. With these calculations, the enhanced $E2$ transitions from the $9/2^-, 7/2^-, 5/2^-, 3/2^-$ states, of about the same magnitude as those for the particle+core multiplets, are reproduced; also, the branching ratios for these states are reasonably well described. The calculated $5/2_1^-$ state in ^{123}Te has the main configuration $88.0\% 4_1^+ \otimes h_{11/2} + 6.7\% 2_1^+ \otimes f_{7/2}$, whereas the $3/2_1^-$ state, associated to the experimental state at 1345 keV can also be interpreted as a member of the $h_{11/2}$ family, having a rather similar structure: $87.5\% 4_1^+ \otimes h_{11/2} + 6.3\% 2_1^+ \otimes f_{7/2}$. It should be emphasized that the experiment indicates an additional small, but sizable p-wave component in this state. Very similar configurations have been obtained for the states of ^{125}Te. Besides the first $9/2^-, 7/2^-, 5/2^-, 3/2^-$ states which can be readily assigned to the experimentally observed ones, the calculated $1/2_1^-$ level is predicted at 1.5 MeV above the parent $11/2^-$ state.

Thus, the configurations of the lowest $5/2^-$ and $3/2^-$ states are mainly those of a $h_{11/2}$ quasiparticle whose spin is antialigned with that of the first 4^+ state of the core. Preliminary calculations for ^{129}Te show a similar situation.

Summarizing, the specific decay mode of the discussed states could be understood if the mutual exchange of the $h_{11/2}$ and $p_{3/2}$, $p_{1/2}$ components both for the initial and final states take place. A coupling of the neutron wave functions with the wave functions of the even-even core gives some preference for the γ deexcitation inside the negative-parity states. The percentage of the main and minor components may be different in each state forming specific γ branchings. Therefore experimentally observed branchings provide an excellent possibility for testing the quality of calculated IBFM wave functions. A detailed analysis is still in progress and will be published in forthcoming papers.

Returning to the photoabsorption data, the seven states in ^{123}Te, namely, at 1345, 1759, 1808, 1978, 2021, 2129, and 2197 keV could be responsible for the first plateau in the (γ,γ') excitation function given in Fig. 3 of Ref. [2]. The further rise of the excitation curve at 2.8 MeV can be caused by the states at 2622 and 2725 keV.

The (γ,γ') excitation function (Fig. 3 of Ref. [2]) for the population of the neighboring ^{125}Te^m provided less details at low energies. Error bars representing the upper level for the activation yield at energies below 4 MeV do not exceed the background base line due to the experimental difficulties of measuring the γ ray of a strongly converted transition at 35 keV. The first significant increase of the activation yield takes place between 4.2 and 4.5 MeV which is beyond the region of the present measurements. This peculiar feature correlates with the spectroscopical picture shown in Fig. 2. Similarly as in case of ^{123}Te the main feeding of the $11/2^-$ isomer goes through the $5/2^-$ state at 1071 keV. In this case contrary to ^{123}Te only the lowest $3/2^-$ states at 1700, 1957, and 2315 keV show appreciable (d,p) population by $l=1$ transitions [17]. This means that other $1/2^-$ and $3/2^-$ states having small p strength could not be considered as important gateways in the (γ,γ') process. The whole experimental (d,p) distribution of the $l=1$ strength above 2.5 MeV in ^{125}Te does not correlate with the behavior of the primary's transitions in the (n,γ) reaction. It should be emphasized that in ^{125}Te an overlapping of $h_{11/2}$ and p wave functions are much smaller than in ^{123}Te. Therefore the deexcitation pattern in ^{125}Te shows less preference to the own negative-parity states.

The anomalous population of the long-lived Te isomers could be understood based on the present comprehensive (n,γ) and (d,p) studies. The principal reason for this phenomenon is connected with the peculiar deexcitation mode of the intermediate states through the lowest isolated $5/2^-$ state. In the frame work of the IBFM this keystone state represents a mixture of the $1h_{11/2}$ neutron wave function as a main component with a minor $3p$ component which are coupled with the even-even bosonic core. These structures being fragmented between many high-lying levels enhance significantly the γ transitions inside the family of the negative-parity states. The direct proof of suggested gateways would be possible in the future studies of nuclear resonance fluorescence in Te nuclei.

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