



# Selective properties of neutron transfer reactions in the $^{90}\text{Zr} + ^{208}\text{Pb}$ system for the population of excited states in zirconium isotopes

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## Abstract

Nuclei produced via multineutron transfer channels have been studied in  $^{90}\text{Zr} + ^{208}\text{Pb}$  close to the Coulomb barrier energy in a fragment- $\gamma$  coincident measurement employing the PRISMA magnetic spectrometer coupled to the CLARA  $\gamma$ -array. The selective properties of the reaction mechanism have been discussed in terms of states and their strength excited in the neutron transfer channels leading to  $^{89-94}\text{Zr}$  isotopes. A strong population of yrast states, with energies up to  $\sim 7.5$  MeV has been observed.

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## 1. Introduction

A significant amount of experimental data on heavy ion transfer reactions collected in the last decade have been shown to be quantitatively described by the reaction model which includes elementary degrees of freedom, surface modes and single particles (see Refs. [1–3] and references therein). It has been demonstrated that through the excitation of these elementary modes, the energy and angular momentum are transferred from the relative motion to these intrinsic degrees of freedom and that mass and charge are exchanged among the two partners of the collision.

The interplay between single particle degrees of freedom and nuclear vibration quanta is fundamental in the description of nuclear structure properties (energy levels and electromagnetic transition probabilities), and the effects of this coupling are of great interest in present nuclear physics. An open question is to what extent, via transfer mechanism, one can populate and study states with such coupling schemes. This subject benefited from the availability of the new generation large solid-angle magnetic spectrometers coupled to powerful  $\gamma$  arrays. This coupling allowed to completely identify nuclei produced via heavy ion multinucleon transfer reactions and to measure associated individual electromagnetic transitions (see Refs. [4,5] and references therein). With the PRISMA–CLARA set-up [6–8] studies have recently addressed the question of particle–phonon coupling properties in Ar and Ca isotopes produced via multinucleon transfer. In the reaction  $^{40}\text{Ar} + ^{208}\text{Pb}$  [9], the interpretation of newly observed states within a particle–phonon coupling picture has been used to consistently follow, via their excitation energies, the evolution of collectivity in odd Ar isotopes. In  $^{48}\text{Ca} + ^{64}\text{Ni}$  [10], evidence has been found, using a weak coupling model, for particle–vibration coupled states in  $^{49}\text{Ca}$  and  $^{47}\text{Ca}$  based on the  $3^-$  phonon of  $^{48}\text{Ca}$ .

In a simple shell model picture, the proton  $p_{1/2}$  orbital is filled in Zr isotopes in the close vicinity of  $N = 50$ . The Zr isotopic chain spans a wide range of neutron numbers, passing the closed and semi-closed neutron shells with the lightest and heaviest stable isotopes,  $^{90}\text{Zr}$  and  $^{96}\text{Zr}$ . The structure of Zr nuclei changes from pure spherical nuclei at the closed shell to strongly deformed ones in the neutron-rich region ([11–14]). Shape coexistence, with different nuclear shapes corresponding to two potential energy minima have also been reported [15]. Many of the lower lying states close to  $^{90}\text{Zr}$  are formed by the excitation of single nucleons, being the present admixtures of different configurations rather small. The presence of these different configurations changes when going towards the more neutron-rich isotopes. The study of this transition between spherical and deformed nuclear shapes, especially by investigating chains of isotopes populated at once, by the same reaction mechanism, can provide additional information.

In the present work we studied, with the PRISMA–CLARA set-up, the population pattern of the excited states of the zirconium isotopes produced via multineutron transfer reactions in  $^{90}\text{Zr} + ^{208}\text{Pb}$ . The total yields for pure neutron transfer channels have been already published in Ref. [16], where experimental data have been compared with the semi-classical model GRAZING [2,17]. This model calculates the evolution of the reaction by taking into account, besides the relative motion variables, the intrinsic degrees of freedom of projectile and target, the isoscalar surface modes and the single-nucleon transfer channels. The multinucleon transfer channels are described via a multi-step mechanism. The relative motion of the system is calculated in a nuclear plus Coulomb field, where for the nuclear part, the Akyüz–Winther potential parameterization has been used. The excitation of the intrinsic degrees of freedom is obtained by employing the

well-known form factors for the collective surface vibrations and one-particle transfer channels. The experimental constant drop of neutron pick-up channels, suggesting an independent particle transfer mechanism, has been well reproduced by calculations (see also [1,18–21]). This good agreement between theory and experiment corroborate the fact that the included degrees of freedom describe well the reaction. It is important to see how would the same degrees of freedom play a role in the selectivity of the population of the excited states. This reaction is well suited since it involves closed or semi-closed shell nuclei, thus we expect that the spectra we are populating with the transfer mechanism will comprise partly of single-particle or single-hole states, collective bosons and their coupling. It is very important to study the origin of collectivity which can be dominated by a few particle–hole components or can be derived from the cooperative action of many configurations.

Here, we focus on the population strength and the structure of the states excited in the  $^{89-94}\text{Zr}$  isotopes, where a few new  $\gamma$  ray transitions have also been consistently incorporated into known level schemes. In this context, a comparison between heavy and light-ion induced reactions has been made.

## 2. The experimental set-up and data analysis

The reaction  $^{90}\text{Zr} + ^{208}\text{Pb}$  has been performed with the XTU-Tandem + ALPI booster accelerator complex of the Laboratori Nazionali di Legnaro. A  $^{90}\text{Zr}$  beam has been delivered at  $E_{\text{lab}} = 560$  MeV with an average intensity of 3 pA onto a  $280 \mu\text{g}/\text{cm}^2$   $^{208}\text{Pb}$  2 mm wide strip target deposited on a  $20 \mu\text{g}/\text{cm}^2$  C-backing. Projectile-like products have been detected at two different angles,  $\theta_{\text{lab}} = 56^\circ$  and  $\theta_{\text{lab}} = 61^\circ$ , with the PRISMA magnetic spectrometer. PRISMA has a solid angle of  $\simeq 80$  msr and a wide momentum acceptance of  $\pm 10\%$ . It consists of a magnetic quadrupole singlet and a magnetic dipole, together with a complex detector system: a micro-channel plate (MCP) [6] at the entrance, and a multi-wire parallel plate avalanche counter (MWPPAC) [7] at the focal plane, both position-sensitive with 1 mm resolutions. The MCP and MWPPAC provide the timing signals, with sub-nanosecond resolution, for the time-of-flight (TOF) determination. They are followed by transverse field multiparametric ionization chambers (IC) [7]. The MWPPAC and the IC are segmented into several sections, to preserve a high resolution even when detection rates overcome several kHz. The size of the IC is sufficient to stop all ions collected at the focal plane, whose kinetic energies may differ by more than 20%, given the large acceptance of the spectrometer. The segmentation of the anode into 40 rectangular sub-anodes allows to optimize the gas pressure in order to get the best nuclear charge resolution.

The described detector system gives all the necessary information for the complete ion identification, which is performed via an event-by-event reconstruction of the trajectory inside the magnetic elements [16,22]. In this reconstruction, the ion trajectories after the quadrupole are assumed to be planar, as a consequence of the fact that the longitudinal dimension of PRISMA is much larger than the transversal one. In addition, due to the large dimensions of the magnetic elements, the fringing fields can be neglected. These assumptions have been carefully checked with the simulation of the ion transport through the spectrometer [22]. The trajectories are, thus, uniquely determined by the known ratio of the quadrupole and dipole magnetic fields, and the bending radius in the dipole (and consequently the total trajectory length), which is the result of the tracking procedure. The known magnetic field of the dipole magnet, the bending radius and total lengths, together with the measured TOF, provide the ratio  $A/q$ , where  $A$  is the atomic mass and  $q$  its atomic charge state. This quantity as a function of the horizontal position at the focal plane displays a characteristic repetitive pattern of the different  $A/q$ , with a broad charge

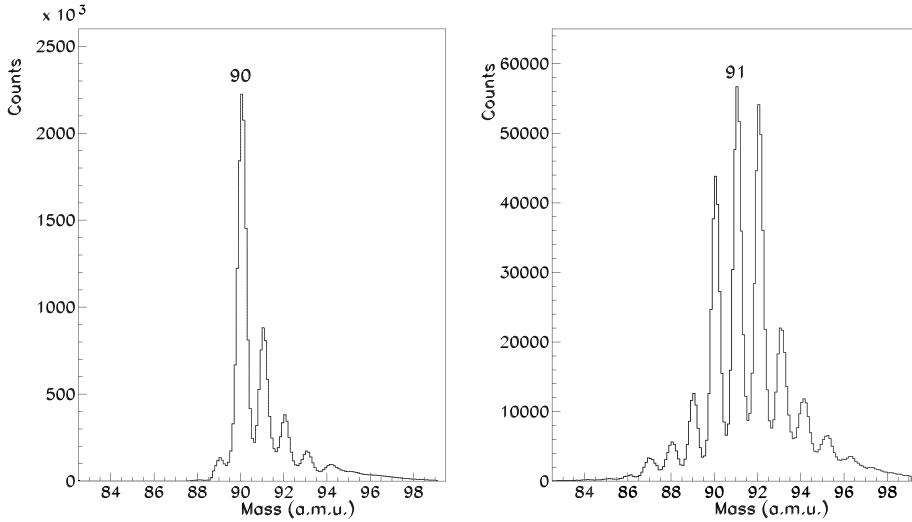


Fig. 1. Mass distribution of Zr isotopes produced in the  $^{90}\text{Zr} + ^{208}\text{Pb}$  reaction at  $E_{\text{lab}} = 560$  MeV. The spectra have been obtained with PRISMA alone (left) and with the condition that at least one  $\gamma$  ray is detected in the CLARA array (right). To show the full statistics, the spectra obtained at both measured angles ( $\theta_{\text{lab}} = 56^\circ$  and  $\theta_{\text{lab}} = 61^\circ$ ) have been added.

state distribution, characteristic of heavy ions. To determine the mass, information on the total energy  $E$  of the ions has been used. This total energy is provided by the IC, which also measures the energy loss  $\Delta E$  for the identification of the nuclear charge  $Z$ .

Fig. 1 shows the Zr mass spectra, where the achieved mass resolution  $\Delta M/M \approx 1/230$  allowed to clearly separate the different isotopes. The spectra are obtained by using PRISMA alone (Fig. 1 left) and with the condition that at least one  $\gamma$  ray is detected with CLARA in coincidence with the selected channel (Fig. 1 right). In this way, the ground-to-ground state transitions are not included in the yield distribution. In the left panel one sees the dominance of neutron pick-up channels, with a weaker population of lower mass channels, as expected from optimum  $Q$ -value arguments.

These lower mass channels are in general of more complex nature, since they can be populated not only via stripping mechanism but also by secondary processes (i.e. neutron evaporation from the primary fragments). They are much better visible when tagging with  $\gamma$  rays, since mass 90 (i.e.  $^{90}\text{Zr}$ ), being dominated by the elastic scattering, is strongly suppressed. One notices also that the relative intensities of pick-up channels, after the transfer of 3–4 neutrons, differ very little between the case with or without  $\gamma$  coincidences, as expected for nuclei populated with higher and higher excitation energy.

The CLARA  $\gamma$ -array [8] consisted of 24 clover detectors placed on a hemisphere centered (covering a solid angle of  $2\pi$ ) at the target position and opposite of PRISMA. Each clover detector was composed of four HP-Ge crystals surrounded by an anti-Compton shield, ensuring a peak-to-total ratio of  $\approx 45\%$ . The total photopeak efficiency was of the order of  $\approx 3\%$  for 1.33 MeV  $\gamma$ -ray energy. The energy resolution obtained after the Doppler correction based on the knowledge of the reconstructed velocity vector in PRISMA was  $\sim 0.6\%$ – $0.9\%$  over the whole velocity distribution of the projectile-like products detected in PRISMA. In the  $\gamma$  spectra, the  $\gamma$  rays belonging to both reaction partners are generally present, i.e. the wrongly Doppler corrected  $\gamma$  rays of the associated binary partner will appear as a very wide peak.

In this reaction, the strongest populated channels are those of the  $^{90,91,92}\text{Zr}$  isotopes, but sufficient statistics has been achieved to analyze the  $\gamma$  spectra of the  $^{89,93,94}\text{Zr}$  isotopes as well. In the following section we will concentrate on the strongest populated states in the Zr isotopes, whose  $\gamma$ -ray spectra are plotted in Fig. 2 (from  $^{89}\text{Zr}$  (top) to  $^{94}\text{Zr}$  (bottom)). The unavoidable partial overlap between near-by masses resulted in a contamination of some Zr spectra, therefore one observes  $\gamma$  rays that do not always belong to the selected isotope. By comparing spectra of different zirconium isotopes with each other, and by comparing them with spectra of yttrium ( $(-1p)$  channels) isotopes, we detected some overlap between near-by charges or masses. To clean spectra in a safe way, we scaled the spectrum that contains a  $\gamma$  ray which has been attributed to the close by isotope or isobar, and subtracted, in the whole energy range, the scaled spectrum from the one of interest. These spectra are presented in Fig. 2. The cleaning procedure does not significantly affect the number of counts for the  $\gamma$  transitions belonging to the detected isotope.

In the discussion of the strongest populated states and their dominant structure, we will take advantage of the already published shell model calculations [23,24]. A few newly observed  $\gamma$  rays will be presented and the level schemes will be updated based mainly on systematics with neighboring nuclei. This method was successfully used in different cases [4,9,25–27], where electromagnetic transitions coming from the decay of specific nuclei have been identified by exploiting the fragment- $\gamma$  coincidence method of the PRISMA–CLARA set-up.

### 3. Results and discussions

Based on the  $\gamma$  rays observed in our measurement, and the assignments found in evaluated data compilations of levels properties for  $^{89}\text{Zr}$  [28],  $^{90}\text{Zr}$  [29],  $^{91}\text{Zr}$  [30],  $^{92}\text{Zr}$  [31],  $^{93}\text{Zr}$  [32] and  $^{94}\text{Zr}$  [33] level schemes have been constructed and updated. In some cases the additional informations were obtained from more recent measurements. For example, results of  $(n, n'\gamma)$  measurements [12,15,34] for  $^{90,94}\text{Zr}$ , or of high-spin states in  $^{91,92}\text{Zr}$  from the  $^{82}\text{Se}(^{13}\text{C}, xn)$  reaction [35]. The level schemes are presented in Figs. 3, 4, and 5 (even–even isotopes) and 7, 8, and 9 (even–odd isotopes). In these figures, the width of the arrow corresponds to the intensity of the observed  $\gamma$  ray, corrected for the efficiency of the CLARA array. In some cases, when excited states have a complex decay pattern, with transitions of different intensities, in the weaker Zr channels we mostly observed only the strongest known decay branch. We carefully checked that the expected number of events for the (not observed) weaker branches is consistent with the observed background level. In the level schemes, dashed lines denote undetected or unresolved  $\gamma$  rays, as for example the 587.8 keV  $\gamma$  decaying from the long lived  $1/2^-$  state in Fig. 7 or the 946.9 keV and 1425.2 keV lines in  $^{93}\text{Zr}$ . Such dashed lines will be justified in the text for each case.

#### 3.1. Even–even Zr isotopes

In general, in the even–even Zr isotopes (Figs. 3, 4 and 5), the strongest observed transitions are those from the decay of yrast states. In particular, in  $^{92}\text{Zr}$  (the  $(+2n)$  channel) states up to spin  $16\hbar$  and excitation energy of about 7.5 MeV were clearly identified. In the negative parity band, strong excitation of  $3^-$ ,  $5^-$  and  $7^-$  states has been observed. Besides the yrast states, only higher order  $2^+$  and  $4^+$  states have been identified, although with lower intensities.

In the construction of the  $^{90}\text{Zr}$  level scheme (Fig. 3) we used information from the  $(n, n'\gamma)$  study [12] when applicable, while for higher spin states we adapted the values tabulated in [29].

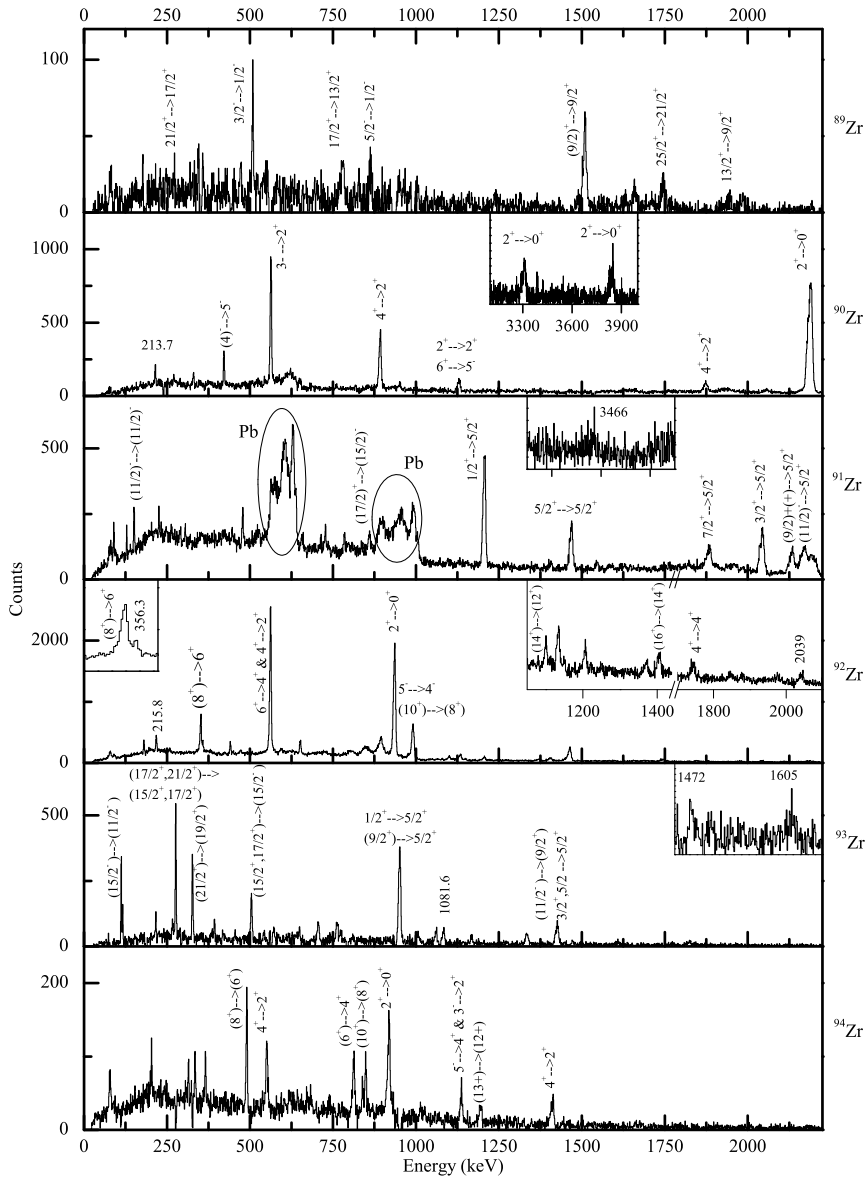


Fig. 2. Doppler corrected  $\gamma$ -ray spectra of the observed Zr isotopes,  $^{89-94}\text{Zr}$  from top to bottom, respectively. Spins and parities of initial and final states of the strongest transitions are tagged. The  $\gamma$  rays which could not be placed in the level scheme are labeled by their energies. Inserts display the enlarged energy region of interest. The wrongly Doppler corrected  $\gamma$  rays of the heavy fragment are also labeled (see text).

For the high-spin levels in  $^{92}\text{Zr}$  we followed the level structure obtained in Ref. [35] through the  $^{82}\text{Se}(^{13}\text{C}, xn)$  reaction. In the construction of the level scheme (see Fig. 4) we took into account that the 559.7 keV line could not be resolved from the much stronger 560.9 keV line from the  $4^+$  at 1495.5 keV. In addition, taking advantages of the fusion–evaporation reaction study [35] we adjusted the relative intensities of the 559.7 keV and 471.4 keV  $\gamma$  lines decaying



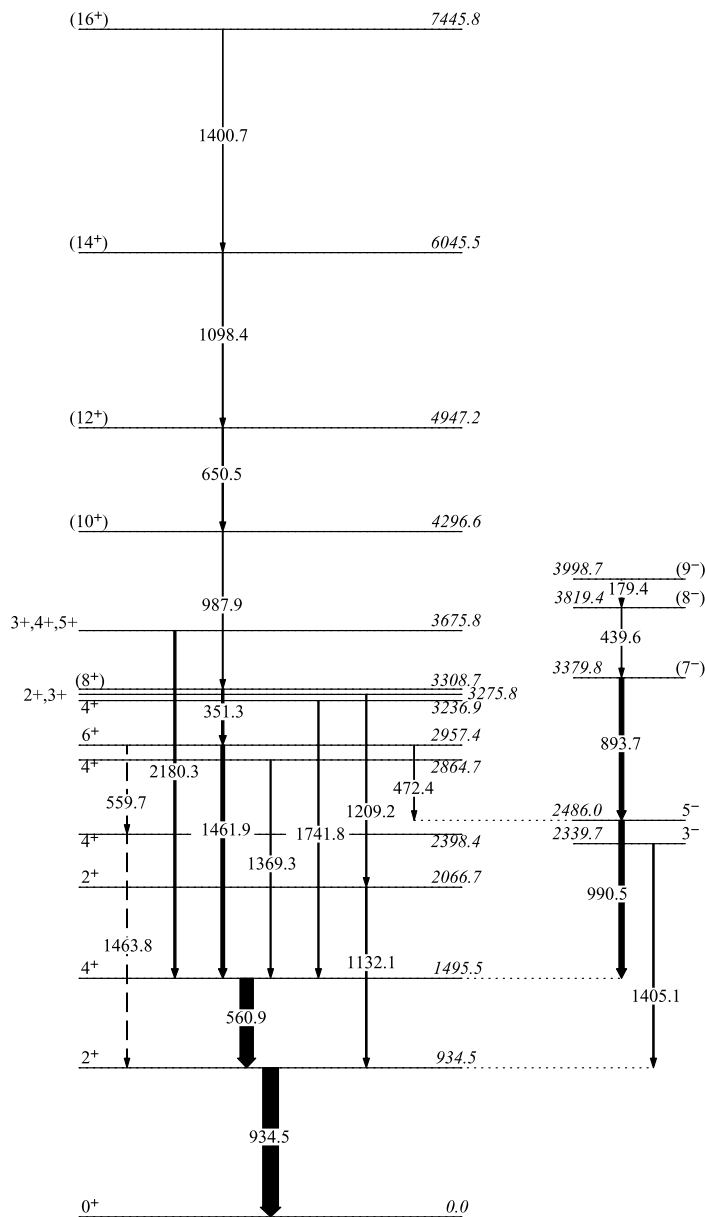


Fig. 4. The experimental positive (left) and negative (right) parity states observed in our measurement for  $^{92}\text{Zr}$ . Relative  $\gamma$ -ray intensities are indicated by the width of the arrow. The energy, spin and parity of levels, their branching ratios, and energy of transitions, are as in Ref. [31] and as in Ref. [35]. The 559.7 keV and 1463.8 keV lines were plotted as dashed lines, as these transitions could not be resolved from the more intense 560.9 keV and 1461.9 keV lines (see text). The level populations are as in Refs. [31,35].

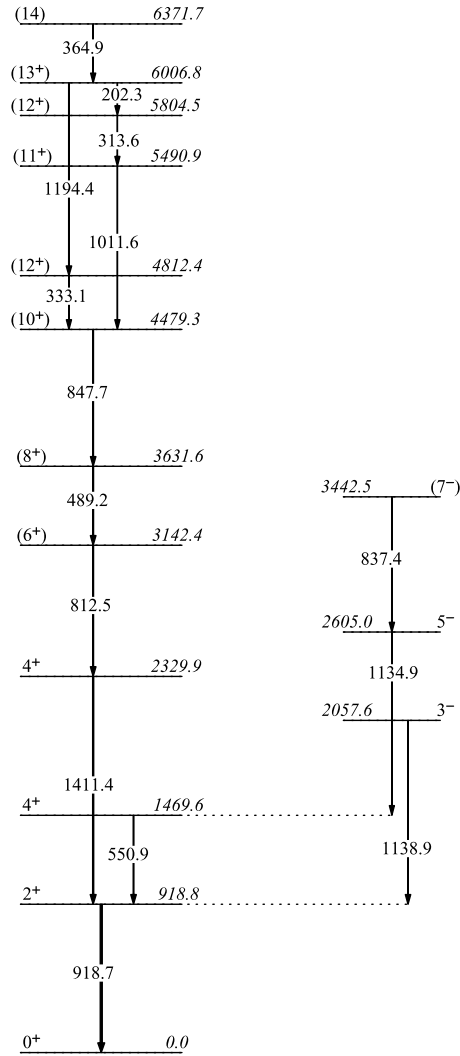


Fig. 5. The experimental positive (left) and negative (right) parity states observed in our measurement for  $^{94}\text{Zr}$ . Relative  $\gamma$ -ray intensities are indicated by the width of the arrow. The properties of these  $^{94}\text{Zr}$  levels are as in Refs. [33,34].

For the  $^{94}\text{Zr}$  level scheme, we used the assignment adopted in the data compilation [33] as well as more recent informations from the  $(n, n'\gamma)$  study [15,34].

In the even–even nuclei, a few new  $\gamma$  transitions have been observed,  $E_\gamma = 213.7(4)$  keV in  $^{90}\text{Zr}$ ,  $E_\gamma = 215.8(4)$  keV,  $356.3(5)$  keV, and  $2039(2)$  keV in  $^{92}\text{Zr}$  (see Table 1).

For the assignment of the new  $\gamma$  transitions, we took advantage of the total kinetic energy loss (TKEL) distribution for each of the discussed transfer channels. The angle integrated total kinetic energy losses are constructed by assuming pure binary reaction. A selection of the populated states can then be achieved by setting different gates on the TKEL distribution, as illustrated in Ref. [16]. Applying the same procedure here, it turned out that the unknown  $\gamma$  transitions  $E_\gamma = 213.7$  keV in  $^{90}\text{Zr}$ , and  $E_\gamma = 215.8, 356.3$  keV in  $^{92}\text{Zr}$ , are more intense for the large

Table 1  
New  $\gamma$  transitions identified in the present  $^{90}\text{Zr} + ^{208}\text{Pb}$  reaction. The first column lists energies of  $\gamma$  rays ( $E_\gamma$ ) obtained in the present measurement. The second and third columns show energies ( $E_i$ ), spins and parities ( $J_i^\pi$ ) of suggested initial states, while energies ( $E_f$ ), spins and parities ( $J_f^\pi$ ) of suggested final states are listed in the fourth and fifth columns. All these later informations come from the different compilation articles (see text).

| Isotope          | $E_\gamma$ (keV) | $E_i$ (keV) | $J_i^\pi$       | $E_f$ (keV) | $J_f^\pi$ |
|------------------|------------------|-------------|-----------------|-------------|-----------|
| $^{90}\text{Zr}$ | 213.7(4)         |             |                 |             |           |
| $^{91}\text{Zr}$ | 3466(3)          | 3469(5)     | $7/2^+$         | 0.0         | $5/2^+$   |
| $^{92}\text{Zr}$ | 215.8(4)         |             |                 |             |           |
|                  | 356.3(5)         |             |                 |             |           |
|                  | 2039(2)          |             |                 |             |           |
| $^{93}\text{Zr}$ | 1081.6(7)        | 2031.4(7)   | $9/2^-, 11/2^-$ | 949.8(6)    | $(9/2^+)$ |
|                  | 1472(1)          | 1463(5)     | $7/2^+, 9/2^+$  | 0.0         | $5/2^+$   |
|                  | 1605(1)          | 1598(5)     | $7/2^+, 9/2^+$  | 0.0         | $5/2^+$   |

energy losses. In  $^{90}\text{Zr}$ ,  $E_\gamma = 213.9$  keV has also been observed in a fusion evaporation study, via the  $^{76}\text{Ge}(^{18}\text{O}, 4n\gamma)^{90}\text{Zr}$  reaction, as a decay of a high-spin and high-excitation-energy state  $(13)^+$  at 7437.8 keV [36]. For  $^{90}\text{Zr}$ , the highest spin and excitation energy state observed in our measurement, for which we were able to follow the cascade towards the ground state is the  $10^+$  state at 5644.0 keV. The states between the  $(13)^+$  at 7437.8 keV and  $10^+$  at 5644.0 keV decay probably via a complex pattern. It is thus very plausible to assume, that the 213.7 keV transition belongs to this high-spin, high-excitation-energy state  $(13)^+$  at 7437.8 keV, even if the complete cascade towards ground state has not been observed. We then argue that all low energy  $\gamma$  transitions,  $E_\gamma = 213.7$  keV in  $^{90}\text{Zr}$ , and  $E_\gamma = 215.8, 356.3$  keV in  $^{92}\text{Zr}$  may come from the decay of higher excitation-energy and high-spin states in  $^{90}\text{Zr}$  and  $^{92}\text{Zr}$ .

To have a better insight into these new  $\gamma$  transitions, we compared, where applicable, the  $\gamma$  spectra with those obtained in the  $^{40}\text{Ca} + ^{96}\text{Zr}$  reaction [16,37]. For this last reaction we have to keep in mind that the Zr spectra correspond to the undetected target-like ions, where the velocity vector has been evaluated assuming a binary reaction. Hence, their  $\gamma$  rays belong to both, the primary binary partner as well as the isotopes produced after evaporation takes place. Therefore the spectra for the same Zr isotopes reached via the two different reactions (stripping in one case or pick-up in the other case) are not necessarily the same. A selected energy region of these two spectra are plotted in Fig. 6.

This energy region has been chosen to better illustrate the different population of high-spin states. It is clearly visible that in the case of the presently studied  $^{90}\text{Zr} + ^{208}\text{Pb}$ , the transitions from higher spin states are more pronounced (see for example the  $(8^+)$  to  $(6^+)$  and the  $(10^+)$  to  $(8^+)$  transitions). A similar situation was observed for other Zr isotopes, in particular for the  $^{92}\text{Zr}$  and  $^{93}\text{Zr}$  isotopes. The fact that in the case of the  $^{92}\text{Zr}$  spectrum of  $^{40}\text{Ca} + ^{96}\text{Zr}$  the 2039 keV line is not so strongly populated favors that these  $\gamma$ -rays result from the decay of high-spin states. The low-lying transitions (215.8, 356.3 keV) were not present in the  $^{92}\text{Zr}$  spectrum from the  $^{40}\text{Ca} + ^{96}\text{Zr}$  reaction, again speaking in favor of their coming from high spins.

3.2. Even–odd Zr isotopes

As for even–even isotopes, the transfer mechanism populates strongly the high-spin states in both, positive and negative parity bands. It is interesting to notice that in the  $^{91}\text{Zr}$  and  $^{93}\text{Zr}$  (being the  $^{89}\text{Zr}$  rather weak channel), above the excitation energy of  $\sim 2.5$  MeV, only the highest known

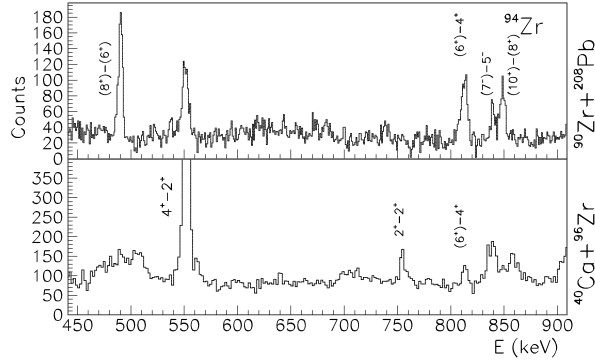


Fig. 6. The  $^{94}\text{Zr}$   $\gamma$  spectra observed in the  $^{90}\text{Zr} + ^{208}\text{Pb}$  reaction (top) and in the  $^{40}\text{Ca} + ^{96}\text{Zr}$  reaction (bottom) [16], for the energy region around 700 keV. The  $4^+ \rightarrow 2^+$  transition is only partially shown (its maximum reaches 1100 counts).

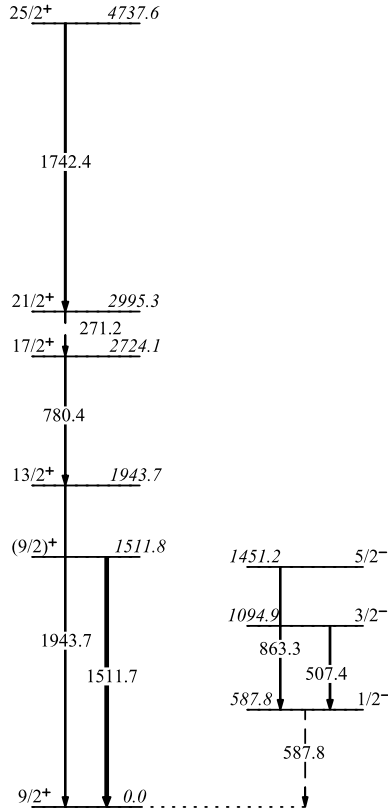


Fig. 7. The  $\gamma$  transitions observed in our measurement for  $^{89}\text{Zr}$ . Relative  $\gamma$ -ray intensities are indicated by the width of the arrow. The level spectroscopy properties are from the data compilation in Ref. [28]. The  $\gamma$ -ray line at 587.8 keV, denoted by a dashed line, decays from the long-lived ( $T_{1/2} = 4.2$  min)  $1/2^-$  state, and thus cannot be observed in our experiment. A weak transition at 271.2 keV, with an intensity that is not consistent with its placement in the level scheme, is also denoted by a dashed line. The higher energy  $\gamma$  rays (at 1742.4 keV and 1943.7 keV) were observed with low statistical accuracy in this rather weak transfer channel, thus their intensity errors are large.

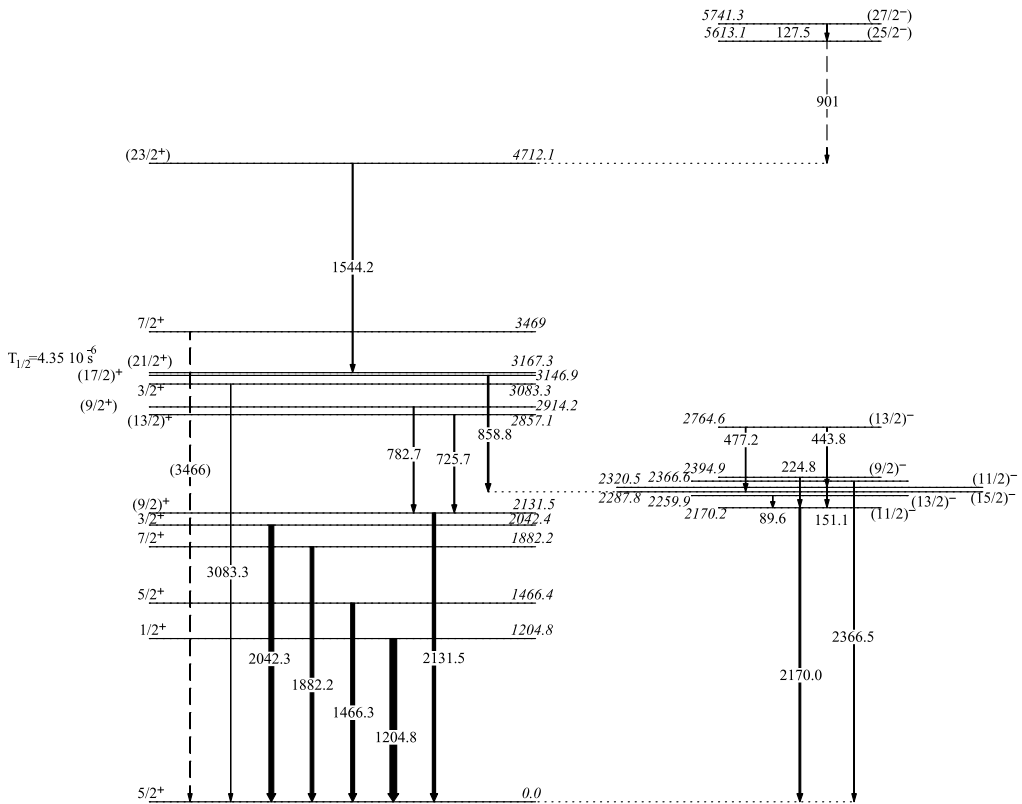


Fig. 8. Experimental positive (left) and negative (right) parity states observed in our measurement for  $^{91}\text{Zr}$ . Relative  $\gamma$ -ray intensities are indicated by the width of the arrow. The level properties are from the data compilation in Ref. [30]. For the higher spins we also used data from Ref. [35]. The intensity of the 901 keV  $\gamma$  transition from the 5613.1 keV state could not be precisely extracted, as it overlaps with wrongly Doppler corrected heavy-partner  $\gamma$  rays. Thus it is plotted as a dashed line, as well as a new 3466 keV  $\gamma$  transition.

spin states have been populated. This strongly speaks in favor of the selectivity of the transfer mechanism for large angular momentum transfers.

In semi-magic  $^{90}\text{Zr}$ , the neutron  $g_{9/2}$  orbital is filled, thus, in even-odd Zr isotopes the ground states are well defined by the position of the unpaired neutron, leading to  $9/2^+$  for  $^{89}\text{Zr}$  and  $5/2^+$  for  $^{91,93,95}\text{Zr}$ . Taking into account the relevant neutron orbitals, one expects that the  $9/2^+$ ,  $1/2^-$ ,  $5/2^-$ ,  $3/2^-$ , and  $7/2^-$  or  $7/2^+$ ,  $5/2^+$ ,  $3/2^+$ ,  $1/2^+$  and  $11/2^-$  states dominate the low-lying spectra of the even-odd Zr isotopes.

Looking more closely at the properties of  $^{89}\text{Zr}$  (see Figs. 2 and 7), one would expect, due to the neutron hole, the dominance of the  $9/2^+$  (ground state),  $1/2^-$ ,  $3/2^-$ ,  $5/2^-$ , and  $7/2^-$  states in the low energy region. These states, except the higher excitation energy  $7/2^-$  state, have been observed (see Fig. 7). In large-scale shell model (SM) calculations [38] the structure of the Zr isotopes was discussed. In these SM calculations the doubly-magic nucleus  $^{100}_{50}\text{Sn}$  was assumed to be an inert core and the nuclei were described in terms of proton and neutron holes distributed in the  $g_{9/2}$ ,  $p_{1/2}$ ,  $p_{3/2}$  and  $f_{5/2}$  orbitals. These calculations demonstrate that the wave-functions of the  $1/2^-$ ,  $5/2^-$  and  $3/2^-$  states (which are exactly the negative parity states observed in our measurement) have large wave function components in which a neutron hole in the  $p_{1/2}$  and

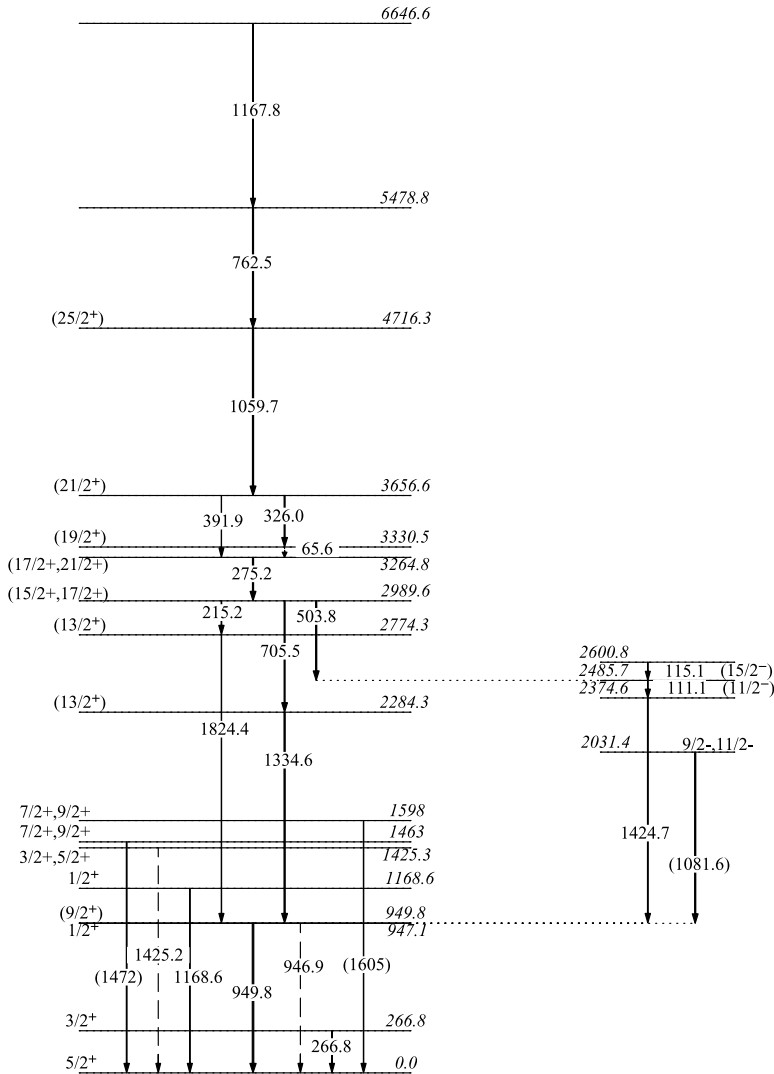


Fig. 9. Experimental positive (left) and negative (right) parity states observed in our measurement for  $^{93}\text{Zr}$ . Relative  $\gamma$ -ray intensities are indicated by the width of the arrow. The spectroscopy properties are from the data compilation reported in Ref. [32]. The newly observed  $\gamma$  rays at 1081.6 keV, 1605 keV and 1472 keV are denoted in parentheses. The 946.9 keV and 1425.2 keV lines are plotted as dashed lines (see text).

$p_{3/2}$  orbitals is coupled to a proton configuration dominated by the  $g_{9/2}$  orbital. Concerning the positive parity band, beside the first excited  $(9/2)^+$  state at 1511.8 keV, we observed a very selective feeding of the high-spin states up to the  $25/2^+$  state, even if the counting rates were small.

In the case of  $^{91,93}\text{Zr}$ , one would expect that the states  $9/2^+$ ,  $7/2^+$ ,  $3/2^+$ ,  $1/2^+$  and  $11/2^-$  will dominate the low excitation energy region, beside the  $5/2^+$  ground state. These states were, indeed, populated, particularly in  $^{91}\text{Zr}$  (see Figs. 8 and 9). To better explore the single-particle properties of  $^{91,93}\text{Zr}$ , we compared the population strengths obtained in the present measurement

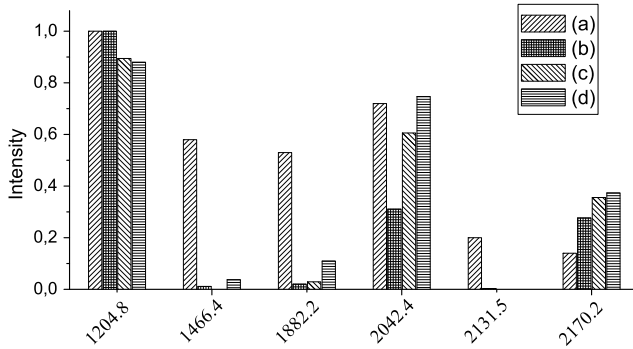


Fig. 10. Intensities of the  $^{91}\text{Zr}$  states below an excitation energy of 2180 keV (labeled with (a)), obtained in the  $(+1n)$  channel of the  $^{90}\text{Zr} + ^{208}\text{Pb}$  reaction. These states are  $1/2^+$  at 1204.8 keV,  $5/2^+$  at 1466.4 keV,  $7/2^+$  at 1882.2 keV,  $3/2^+$  at 2042.4 keV,  $(9/2)^+$  at 2131.5 keV and  $(11/2^-)$  at 2170.2 keV. Data labeled (b), (c), and (d) have been extracted from the  $(d, p)$  reactions from Refs. [39–41], respectively.

with those from the  $(d, p)$  reactions for  $^{91}\text{Zr}$  [39–41] and for  $^{93}\text{Zr}$  [42]. These  $(d, p)$  reactions are in fact well suited to probe single particle properties. This comparison for  $^{91}\text{Zr}$  is shown in Fig. 10. The population strength of the  $^{91}\text{Zr}$  levels, with excitation energy up to  $\sim 2$  MeV (see Fig. 10), has been obtained by subtracting the feeding from above in agreement with the level scheme of Fig. 8, and correcting for the efficiency of the CLARA array. The intensity of each transition was normalized to the strongest transition (from  $1/2^+$  to  $5/2^+$ ). The  $^{90}\text{Zr}(d, p)^{91}\text{Zr}$  reactions data have been extracted from the measured cross sections of the observed states [39–41].

A similar comparison has been carried out between the states of  $^{93}\text{Zr}$  populated via the  $(+3n)$  channel in the present  $^{90}\text{Zr} + ^{208}\text{Pb}$  reaction and in the  $^{92}\text{Zr}(d, p)^{93}\text{Zr}$  reaction [42]. The analysis was also carried out for the energy level  $E_{\text{ex}} = 2025(10)$  keV ( $9/2^-$ ,  $11/2^-$ ) [28] whose decay was unknown, and to which we attributed a newly observed  $\gamma$ -decay with  $E_{\gamma} = 1081.6$  keV. According to such  $\gamma$ -decay, the energy of the state  $9/2^-$ ,  $11/2^-$  is 2031.4(7) keV. i.e.  $\sim 6$  keV higher than reported in the literature [28].

In these comparisons we observed that the  $1/2^+$  and  $3/2^+$  states in  $^{91}\text{Zr}$  have similar strengths in both, light and heavy ion induced reactions, while the higher spin states,  $5/2^+$ ,  $7/2^+$  and  $9/2^+$  are strongly excited in the  $^{90}\text{Zr} + ^{208}\text{Pb}$  reaction. In contrast to light-ion induced reactions, negative parity states are strongly populated in heavy-ion transfer. Concerning the negative parity states in the  $(d, p)$  reaction, only the  $(11/2)^-$  at 2170.2 keV has been populated. In the case of  $^{93}\text{Zr}$ , the positive parity states  $7/2^+$ ,  $9/2^+$  (at 1598 and 1463 keV) have similar strengths as in the light ion induced reactions, while the state  $9/2^-$ ,  $11/2^-$  was strongly populated in our heavy-ion induced reaction.

In the shell-model calculations [24] carried out within the model space  $(1f_{5/2}, 1p_{1/2}, 2p_{3/2}, 1g_{9/2})$  for protons and  $(2d_{5/2}, 3s_{1/2}, 2d_{3/2}, 1g_{7/2}, 1h_{11/2})$  for neutrons the single-particle components of the low-lying states in  $^{91}\text{Zr}$  were discussed. It was demonstrated that the unpaired neutron occupies predominately a single orbital (occupation probability  $> 0.88$ ), confirming the strong single-particle character of the low-lying  $1/2^+$ ,  $5/2^+$  and  $7/2^+$ . It is interesting to notice that the occupation probability for the first  $1/2^+$  state in the  $\nu s_{1/2}$  orbital is 0.976, and for the first  $5/2^+$  states (the ground state and the first  $5/2^+$  excited state) in  $\nu d_{5/2}$  is  $> 0.98$ . The first  $7/2^+$  state has mostly contributions from the neutron  $d_{5/2}$  orbital in its wave function, too (occupation probability 0.885) with only a small contribution of the  $\nu g_{7/2}$  orbital (0.1). The pure  $\nu g_{7/2}$  single particle state is expected at higher energies.

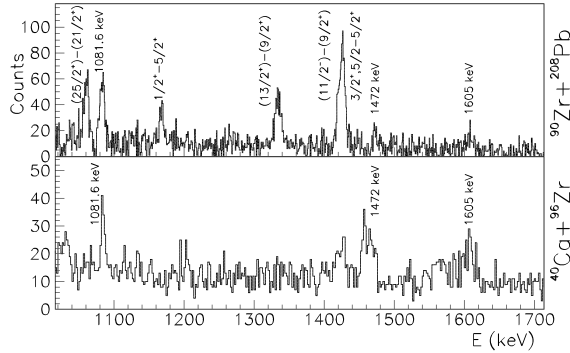


Fig. 11. The  $^{93}\text{Zr}$   $\gamma$  spectra observed in the  $^{90}\text{Zr} + ^{208}\text{Pb}$  reaction (top) and in the  $^{40}\text{Ca} + ^{96}\text{Zr}$  reaction (bottom), for the energy region around 1200 keV.

New  $\gamma$  transitions have also been observed in the even–odd isotopes, 3466(3) keV in  $^{91}\text{Zr}$ , 1081.6(7) keV, 1472(1) keV and 1605(1) keV in  $^{93}\text{Zr}$  (see Table 1). The 1081.6 keV, 1472 keV and 1605 keV lines were also present in the  $^{93}\text{Zr}$  spectrum in the  $^{40}\text{Ca} + ^{96}\text{Zr}$  reaction (see below). The 3466 keV  $\gamma$  ray in  $^{91}\text{Zr}$ , based on the energy difference between known energy levels, could be attributed to the transition from the 3469(5) keV level ( $7/2^+$ ) to the ground state. This state has been populated with a similar strength as the  $7/2^+$  state, in light-ion induced one neutron transfer reactions ( $(\alpha, ^3\text{He})$ ,  $(d, p)$ ,  $(^{12}\text{C}, ^{11}\text{C})$  [40,41,43,44]) and in  $(\alpha, \alpha')$ ,  $(p, p')$ ,  $(d, d')$  scattering measurements. This state probably corresponds to the  $\nu g_{7/2}$  state, and its strong excitation is expected in the one neutron transfer reaction. In a very recent measurement [39] where the states in  $^{91}\text{Zr}$  were populated via the  $(d, p)$  and  $(\alpha, ^3\text{He})$  reactions, a  $7/2^+$  state has been reported at 3475(5) keV, that could be the same state as observed before at 3469(5) keV.

Looking at the neighboring odd Zr isotopes of  $^{93}\text{Zr}$ , where the  $7/2^+$  state decays to the ground state, we suggest that the  $\gamma$ -ray line at 1605(1) keV stems from the decay of the known  $7/2^+$ ,  $9/2^+$  level at 1598(5) keV to the ground state. This state,  $7/2^+$ ,  $9/2^+$  at 1598 keV was populated in the one neutron pick-up ( $^{92}\text{Zr}(\alpha, ^3\text{He})$ ,  $^{92}\text{Zr}(d, p)$ ) and stripping ( $^{94}\text{Zr}(d, t)$ ) reactions. The neutron pick-up reaction also (even with a large spectroscopic factor) populated the same spin-parity state at 1463(5) keV. The energy of our 1472 keV  $\gamma$  ray is close to the possible transition to the ground state, although outside the quoted error.

Taking into account the energy difference of adopted levels, the same transition, 1472 keV, could also be attributed to the decay of a known state with tentative spin and parity assignment  $(1/2^+, 3/2, 5/2^+)$  at 1470.1 keV. This can be excluded as the strongest decay transition of this state at 1203 keV was not observed in our measurement.

In addition, we attributed the 1081.6 keV transition to the decay from the lowest negative parity state  $9/2^-, 11/2^-$  at 2031.4 keV. We found that these new transitions in the  $^{93}\text{Zr}$  spectra show up more clearly for the low-energy part of TKEL. These attributions agree well with the similar excitation pattern observed in  $^{91}\text{Zr}$ .

We would like to comment some of the observed  $\gamma$  rays for which a different placement in the level scheme was possible. The observed  $E_\gamma = 949.8$  keV in  $^{93}\text{Zr}$  can accommodate  $E_\gamma = 946.9$  keV (from  $1/2^+$  at 947.1 keV) and 949.8 keV (from  $(9/2^+)$  at 949.8 keV). The similar situation appears for  $E_\gamma = 1424$  keV, as a decay of  $3/2^+, 5/2^+$  at 1425.3 keV or of  $(11/2^-)$  at 2374.6 keV. All these transitions are included in our level schemes, but plotting the less probable transitions as dashed lines.

We also compared the  $^{93}\text{Zr}$  spectrum with the one obtained in the  $^{40}\text{Ca} + ^{96}\text{Zr}$  reaction [16,37]. This comparison, for the energy range of interest, is shown in Fig. 11. The 1605 keV transition appears stronger in the  $^{40}\text{Ca} + ^{96}\text{Zr}$  reaction, while the 1081.6 keV and 1472 keV lines are of similar intensity in both reactions. Here we would like to remind about our previous finding concerning the  $(11/2^-)$  state in  $^{95}\text{Zr}$  populated in the same  $^{40}\text{Ca} + ^{96}\text{Zr}$  reaction, where we reported the  $E3$  transition of the  $(11/2^-)$  state at 2021.6 keV [16]. The same state was also populated in the fusion–fission reactions [45,46]. The strong population of the  $11/2^-$  state in all studied Zr isotopes will be discussed in more details in the following paragraph.

#### 4. Some considerations on feeding patterns in MNT

In the  $^{90}\text{Zr}$  inelastic channel, a very strong population of the first  $2^+$  state has been observed, as well as a strong feeding of the first  $4^+$  and  $3^-$  states (see Fig. 3). It is interesting to notice that for an excitation energy up to  $\sim 3800$  keV, we observed the decay of almost all known states, while above it only high-spin states have been excited, in particular the  $10^+$  state at 5644.0 keV.

In the  $^{89}\text{Zr} (-1n)$  transfer channel, we observed the negative parity low lying states described with a neutron hole, and a positive parity yrast band on the  $9/2^+$  ground state up to  $25/2^+$  (see Fig. 7). In the  $^{91}\text{Zr} (+1n)$  channel we observed a strong excitation of the positive parity low lying spin states of single particle nature. One may say here that, even if we are dealing with the collision of two heavy nuclei, a strong population of states of single-particle character is still present. At higher excitation energy, positive parity yrast states have been predominantly populated, up to the  $(23/2^+)$  spin [35] (see Fig. 8). In addition, negative parity states, in particular the  $(11/2^-)$  at 2170.2 keV, have been strongly fed.

In  $^{92}\text{Zr}$ , positive and negative parity yrast states are selectively and strongly populated (see Fig. 4). In comparison with the heavy-ion fusion–evaporation reaction [35] the same yrast states (positive and negative parity) up to spin  $(16^+)$  are strongly excited in our reaction. The situation is very similar for the more neutron transfer channels,  $^{93}\text{Zr}$  and  $^{94}\text{Zr}$ , where a well developed positive parity yrast band has been observed up to spin  $\sim 15$  (see Figs. 5 and 9). To illustrate the selectivity of the transfer reactions, it is interesting to compare the here populated  $^{94}\text{Zr}$  states with these populated in the  $(n, n', \gamma)$  study [15], where, as expected, more states are excited, but few are with high spins. Such yrast state feeding speaks in favor of a large angular momentum transfer in transfer reactions, more pronounced when more neutrons are transferred. This once more demonstrates the possibility offered by heavy-ion induced transfer reactions in the studies of moderately high-spin states. The observed population of states with high excitation energy and spin is closely connected with the character of the transfer mechanism, which, at this energy close to the Coulomb barrier tends to maximize the transferred angular momentum [1]. A similar situation has also been observed for lighter systems [4,16,26].

A detailed knowledge of the medium and high-spin states may provide a better understanding of the transition between spherical and deformed nuclear shapes going towards more neutron rich Zr isotopes as higher lying orbitals are filled. In this sense it is very convenient to look more closely at the main structure of the populated  $11/2^-$  states, which may be very important to establish the location of the  $\nu h_{11/2^-}$  orbital. Being the more neutron rich Zr isotopes difficult to reach, the knowledge about the position and decay pattern of the  $11/2^-$  states is not always experimentally established.

These findings are important for the theoretical calculations, as they provide an evolution of the single-particle fields, going towards more neutron rich nuclei. In the recent SM calculations [23], the evolution of the  $11/2^-$  states in Zr isotopes was extensively discussed. The largest

uncertainties are in the high-spin states involving excitations of the  $h_{11/2}$  orbital. These calculations were performed in an extended model space ( $1f_{5/2}$ ,  $2p_{1/2}$ ,  $2p_{3/2}$ ,  $1g_{9/2}$ ) for protons and ( $2d_{5/2}$ ,  $3s_{1/2}$ ,  $2d_{3/2}$ ,  $1g_{7/2}$ ,  $1h_{11/2}$ ) for neutrons, i.e. a  $^{78}\text{Ni}$  core. A fair agreement with experiment is found in  $^{91,93,95}\text{Zr}$  for all calculated states. In  $^{91}\text{Zr}$ , it has been demonstrated that the first  $11/2^-$  state (at  $\sim 2.1$  MeV, experimentally and theoretically) has a dominant  $\pi(p_{1/2}^1 g_{9/2}^1) \nu(d_{5/2}^1)$  component (55%), while the total number of neutrons in the  $h_{11/2}$  orbital was calculated to be only 0.16. The dominant configuration for the first  $11/2^-$  state at  $\sim 2$  MeV in  $^{93}\text{Zr}$  turned out to be very similar:  $\pi(p_{1/2}^1 g_{9/2}^1) \nu(d_{5/2}^3)$  with an  $h_{11/2}$  orbital occupancy of 0.27. It is only in  $^{97}\text{Zr}$  that the calculated low-lying  $11/2^-$  level acquires a single-particle nature, due to the  $d_{5/2}$  closure. Thus, we may conclude that a relatively strong excitation of the  $11/2^-$  states is not due to their single-particle nature.

In the same SM calculations, the structure of the  $2^+$  states was extensively discussed. Recent studies [14,15,47–50] show that in several  $N = 52$  and  $N = 54$  nuclei, so-called mixed symmetry states (proton–neutron isovector excitations of vibrational nature) have been observed. Such states may serve as a sensitive probe of the interplay between the proton–neutron degrees of freedom. In  $^{92,94}\text{Zr}$ , however, the calculated structure of the first excited  $2^+$  state corresponds predominantly to a neutron excitation (85% in both nuclei) [23]. These are exactly the states which were strongly excited in our measurement. The second  $2^+$  states have a different structure involving the proton components [13,23]. The experimental findings show a strong  $M1$  and a rather weak  $E2$  transition for the  $2_2^+$  state in  $^{92}\text{Zr}$ , while a different behavior for the  $2_2^+$  state in  $^{94}\text{Zr}$  was reported [48]. This puzzling situation was untangled with additional measurements of lifetimes and weak decay branches [15,34], demonstrating that in order to conclude about the underlying structure one needs various experimental informations. In our neutron transfer reactions, we did not observe the population of these second excited  $2^+$  states in  $^{92,94}\text{Zr}$  at 1847.3 keV and 1671.4 keV, respectively. Although, we observed a rather weak population of the higher lying  $2^+$  states in  $^{92}\text{Zr}$ . A similar situation can be found with the first excited  $0^+$  states, which, for example in  $^{92}\text{Zr}$  has a strong component of proton excitations. We did not observe possible decays of excited  $0^+$  states of  $^{92,94}\text{Zr}$ , similarly to the  $2_2^+$  case.

In the even–even Zr isotopes, the low-energy part of the spectrum is dominated by the first  $2^+$  and  $3^-$  states. Being the excitation of these  $2^+$  states very strong in all even–even isotopes, we tried to explore the structure in the even–odd isotopes in terms of a valence neutron coupled to the strongly excited states of the neighboring even–even core. One should keep in mind that such coupling scenario would be a very simplified description of the structure of these states, but still can be a useful guide. The character of the states which originate from coupling of the “extra” neutron to these  $2^+$  and  $3^-$  states in  $^{91}\text{Zr}$  was discussed in earlier SM calculations [41]. It was concluded that states with the same spin and parity, but based on different core states, mix strongly with each other and with single-particle states, and that the simple weak coupling model cannot be applied in the case of  $^{91}\text{Zr}$ , especially for the coupling to the first  $3^-$  state. In the case of the  $^{91}\text{Zr}$  and  $^{93}\text{Zr}$  nuclei, when coupling the  $5/2^+$  ground states to the first  $2^+$ , one expects a multiplet  $9/2^+$ ,  $7/2^+$ ,  $\dots$ ,  $1/2^+$ , while when coupling to the first  $3^-$ , one expects a  $11/2^-$ ,  $9/2^-$ ,  $\dots$ ,  $1/2^-$  multiplet. The reaction mechanism does not populate the components of the two multiplets uniformly, but generally favors the stretched configurations,  $9/2^+$  and  $11/2^-$ . The same argument holds for  $^{89}\text{Zr}$ , where coupling of its  $9/2^+$  ground state to  $2^+$  and  $3^-$  would result in  $13/2^+$  and  $15/2^-$  stretched configurations, respectively. The properties of such coupled states should be to a large extent determined by the properties of the corresponding core states. The first properties to check would be their excitation energy, thus we plotted in Fig. 12 the

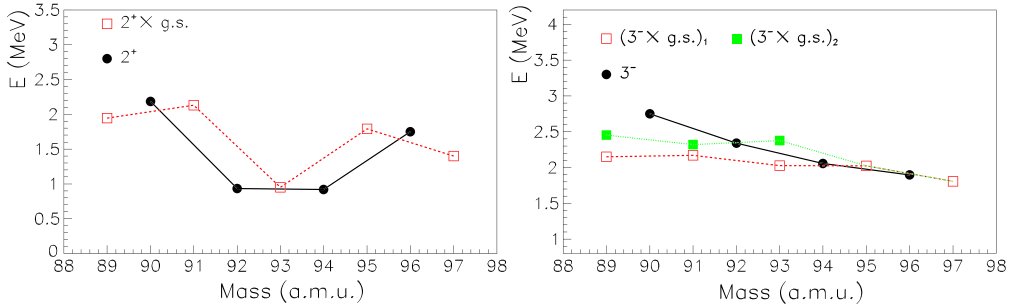


Fig. 12. Left panel: energies of the first 2<sup>+</sup> states (solid circles) in even–even Zr isotopes, together with energies of the 13/2<sup>+</sup> state in <sup>89</sup>Zr, 9/2<sub>1</sub><sup>+</sup> states in <sup>91,93,95</sup>Zr and 5/2<sup>+</sup> in <sup>97</sup>Zr (open squares). Right panel: energies of the first 3<sup>-</sup> states in even Zr isotopes (solid circles), and energies of the first 15/2<sub>1</sub><sup>-</sup> in <sup>89</sup>Zr, 11/2<sub>1</sub><sup>-</sup> in <sup>91,93,95</sup>Zr and 7/2<sub>1</sub><sup>-</sup> in <sup>97</sup>Zr (open squares), and the second 15/2<sub>2</sub><sup>-</sup> in <sup>89</sup>Zr, 11/2<sub>2</sub><sup>-</sup> in <sup>91,93</sup>Zr (solid squares). Lines are only to guide the eye.

energies of the first 2<sup>+</sup> and 3<sup>-</sup> states in even–even Zr isotopes, together with the energies of the states with the expected stretched configuration of these coupled states.

Concerning their decay pattern, all the 2<sub>1</sub><sup>+</sup> states in <sup>90,92,94,96</sup>Zr decay to the ground state with the  $B(E2)$  ranging from 0.055  $e^2b^2$  in <sup>96</sup>Zr to 0.083  $e^2b^2$  in <sup>92</sup>Zr. The decay pattern of the first 3<sup>-</sup> states changes considerably when going from <sup>90</sup>Zr to <sup>96</sup>Zr. The strongest decay branch is via the  $E1$  transition to the first 2<sup>+</sup> state, while the  $E3$  branchings range from 5% to 20% with the corresponding  $B(E3)$  from 0.07 to 0.20  $e^2b^3$ . Such decay pattern persists in the case of <sup>95</sup>Zr [16, 42, 45], where the branchings between  $E1$  (100%) and  $E3$  (20%) transitions from the (11/2<sup>-</sup>) state at 2021.6 keV are very similar to the ones observed in <sup>96</sup>Zr. In <sup>89</sup>Zr, the known decay of the first 15/2<sup>-</sup> state at 2150.6 keV is predominantly through  $E_\gamma = 29.3$  keV, a  $\gamma$  ray energy too low for detection with CLARA. Regarding <sup>93</sup>Zr, the decay pattern of the adapted 11/2<sup>-</sup> states is not well established. From the known decays, we observed an  $E1$  transition of the (11/2<sup>-</sup>) state at 2374.6 keV. In addition, we attributed the 1081.6 keV  $\gamma$  ray to an  $E1$  transition of the 9/2<sup>-</sup>, 11/2<sup>-</sup> (preferably 11/2<sup>-</sup>) state at 2031.4 keV. In <sup>91</sup>Zr we observed the decays of the 11/2<sup>-</sup> states at 2170.2 keV and 2320.5 keV. The energies of these discussed states (see also Fig. 12) do not behave as expected from a simple coupling picture. Among possible qualitative explanations, the 3<sup>-</sup> states may correspond to a complex superposition of cross shell excitations (see also Ref. [23]), which produce a strong mixing of different configurations. One can hardly make conclusions about the nature of these states from the excitation energy information only, especially for complex wave functions. Additional measurements of other relevant properties, such as the strength of electromagnetic transitions, are required.

## 5. Summary

Multinucleon transfer reactions have been studied in the <sup>90</sup>Zr + <sup>208</sup>Pb system close to the Coulomb barrier energy with the PRISMA–CLARA set-up. This fragment- $\gamma$  coincident measurement uniquely attributes electromagnetic transitions to each nucleus identified in the PRISMA spectrometer. A thorough examination of the  $\gamma$  spectra revealed  $\gamma$  transitions not previously reported, which, whenever possible, have been incorporated into known level schemes mainly on the basis of systematics with neighboring nuclei.

The total yields for pure neutron transfer channels agree well with the results of the GRAZING calculation, which beside the evolution of the relative motion, takes into account the intrinsic

sic degrees of freedom of projectile and target, employing the well-known form factors for the collective excitation and the one-particle transfer channels. Presented results generally support multinucleon transfer as a mechanism able to selectively populate some excited states. In almost all observed nuclei most of the excited states have been identified with yrast states, confirming that multinucleon transfer is suitable mechanism to populate high-spin and energy states. In the few nucleon transfer channels a strong excitation of states of single particle nature was observed. For the strongly excited states we investigated the possibility of the coupling of the ground state of the even–odd Zr nuclei to the first  $2^+$  or  $3^-$  in the stretched configuration. The results show that in most of the studied isotopes, the decay modes and the energies of the  $2^+$  states in even isotopes are similar to the corresponding ones in odd isotopes, expected from a such coupling. In the case of the coupling to the  $3^-$  state, the tabulated decays are not so well established, and, due also to a strong mixing of different configurations, the fermion–boson picture does not clearly show up, especially close to  $^{90}\text{Zr}$ .

The selectivity properties of multinucleon transfer reactions, here investigated for well studied nuclei in the valley of stability, will bring valuable information for studies of more exotic regions in the nuclear landscape populated via the same mechanism.

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