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Identification of excited states in the $N=Z$ nucleus ^{68}Se with cluster detectors

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A first level scheme of ^{68}Se with five states up to 4.2 MeV excitation energy and tentative spins 6^+ and 7^- has been established from $\gamma\gamma\gamma$ coincidences measured with six EUROBALL Cluster detectors in close geometry. The level scheme is interpreted in comparison with neutron deficient nuclei of the $A\approx 70$ region and cranking model calculations. In a similar experiment a triple coincidence between the ^{72}Kr transitions 710, 611, and 792 keV has been proven. [S0556-2813(98)50207-5]

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Neutron deficient nuclei with $A\approx 70$ and $N\approx Z$ show many fascinating features. Large prolate and oblate deformations ($\beta_2\approx +0.45$, -0.30) and prolate-oblate shape coexistence at low spins occur in this mass region [1–7]. The observed strong shape variation as a function of particle number, excitation energy, and spin has been interpreted as resulting either from stabilizing energy gaps between the single-particle states at large deformations [8], or from the proton-neutron (pn) interaction acting among the valence nucleons [9,10]. Because of these spectacular shape effects, produced by well-deformed and spherical shell-model states, the resulting strong variation of collective properties makes the neutron-deficient nuclei in the $A\approx 70$ region a favorite testing ground for theoretical approaches [11]. Here, in the heaviest $N=Z$ nuclei accessible without radioactive beam facilities, especially the isospin $T=0$ and $T=1$ components of the pn interaction can be studied. The $T=0$ component is deemed to be primarily responsible for configuration mixing and the onset of collectivity in heavy nuclei [10]. In the $2s1d$- and $2p1f$-shell $N=Z$ nuclei, the $T=0$ component is stronger than the $T=1$ component [12] and causes ground-state spins $I\neq 0$ in the $N=Z$ odd-odd nuclei. In medium mass $N=Z$ nuclei, the $T=0$ coupling is predicted to increase with rotational frequency and affects the moment of inertia and alignment frequencies [12]. In ^{74}Rb an excited and presumably odd-spin band is interpreted to have $T=0$ [13]. Therefore, it is of general interest to investigate isospin effects in medium mass $N=Z$ nuclei.

Both the $N=Z$ nuclei ^{68}Se and ^{72}Kr lie at the borderline between modest γ-soft (e.g., ^{64}Ge [14]) and strong prolate deformations (e.g., ^{76}Sr [15], ^{80}Zr [16]). In several nuclei with N or $Z\approx 36$ prolate-oblate shape coexistence has been observed. The first example of shape coexistence in the mass region $A\approx 70$ was found in ^{72}Se [17]. The level schemes of ^{70,72}Se show level repulsion arising from the interactions between prolate and oblate deformed states [17,3]. For the $g_{9/2}$ bands in ^{69,71}Se, collective oblate deformation has been deduced from the positive sign of mixing ratios in combination with a strongly coupled $K=9/2$ band [4]. So far in the whole mass region an oblate deformation stable against rotation has been very elusive. For the ground state of ^{72}Kr, an oblate deformation should be stabilized by a gap between single-particle states at $N,Z=36$ [8], and various theoretical approaches, indeed, predict an oblate shape [8,18,19]. The level schemes of $^{73-75}$Kr have been interpreted in the frame of shape coexistence [7,20,6]. At $N,Z=34$ two competing gaps in the single-particle energy spectrum [8] may stabilize small oblate as well as small prolate deformations. The aim of the present work was to test whether the predicted octupole softness [21] and oblate deformation [22] can be found in ^{68}Se.

First experimental information on ^{72}Kr transitions was obtained a decade ago, when six transitions of 115, 324, 613, 709, 790, and 925 keV were assigned to ^{72}Kr [23] using the Daresbury recoil mass separator. Inferred from relative intensities and the coincidence between the strongest two transitions a level scheme was suggested [23]. The coincidence between the 613 and 709 keV transition was confirmed by [24].

A few years later, three transitions were assigned to the $N=Z$ nucleus ^{68}Se by Lister *et al.* using the Daresbury recoil mass separator: 343, 854 and 1088 keV [15]. So far no level scheme could be established. Two of the three transitions occur also in ^{68}As (344 and 854 keV), a nucleus populated in every fusion-evaporation reaction which can be used to produce ^{68}Se.

We found a first hint on an 854–1088 keV coincidence in the data of a ^{69}Se study [4]. But, the cross section for ^{68}Se in the used reaction ^{32}S(100 MeV)+^{40}Ca is only minute. In

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fact, the largest part of the 1088 keV transition intensity seemed to belong to the very strong $3p$ channel ^{69}As. Fortunately, the channel ^{69}As is not populated in the reaction ^{58}Ni+^{12}C. Using this reaction and gating on the undisturbed 1088 keV transition thus provides a unique chance to build a level scheme of ^{68}Se without employing a particle trigger.

To establish the level schemes of ^{68}Se and ^{72}Kr, a large γ-ray detection efficiency was used employing six Cluster detectors [25] developed for the EUROBALL spectrometer. Each Cluster detector is composed of 7 encapsulated [26] Germanium crystals in a common cryostat. The six Cluster detectors were arranged in close geometry as a cube (CLUSTER CUBE) with two Cluster detectors in 90° above and below the beam line (see Fig. 9 in [25]). The target was placed in the center of the cube and the beam entered between the two backward detectors positioned at 135° and 225°. The compact geometry required the experiment to be performed without escape-suppression side shields, but the back-catcher BGO crystals behind the encapsulated Ge crystals were used during the ^{68}Se experiment in order to have some Compton suppression. The full energy peak efficiency at $E_\gamma = 1.3$ MeV, provided by 42 Ge detectors, each with a relative efficiency of 60% compared to a $3'' \times 3''$ NaI detector, was $P_{\mathrm{Ph}} \approx 13\%$ including the add-back of Compton scattered events. With an average distance of 11 cm between the target and the front side of the Cluster Ge detectors, the resulting solid angle of 65% of 4π guaranteed the large efficiency required for the investigation of $N=Z$ nuclei with $A \approx 70$. As a consequence of the large solid angle per encapsulated detector of about 0.06π, the recoil velocity should be minimized to reduce Doppler broadening, and the γ-multiplicity M_γ should be less than 10 to reduce sum-up events. Both goals were achieved by using projectiles as light as possible. We studied the reactions ^{58}Ni(^{12}C,$2n$)^{68}Se at 40 MeV and ^{58}Ni(^{16}O,$2n$)^{72}Kr at 55 MeV at the accelerator facility of the Max-Planck-Institut für Kernphysik in Heidelberg. The projectile energies were chosen only slightly above the Coulomb barrier to maximize the relative cross section of the $2n$ channel, and either target consisted of a 99.8% enriched ^{58}Ni foil (^{68}Se experiment: 1.6 mg/cm^2; ^{72}Kr: 0.5 mg/cm^2) rolled onto a thick Bi backing to stop the residual nuclei.

During the first—the ^{72}Kr—experiment the counting rate was 12000 counts/s per single encapsulated Ge detector. At an accepted event rate of 7000 s^{-1} we wrote 2.9×10^9 $M_\gamma \geqslant 3$ coincidences on tape. In the ^{68}Se experiment pileup and accidental events were reduced by the back-catcher BGO, by a slightly larger distance of 12 cm, as well as by a lowering of the counting rate to 6500 s^{-1} per single encapsulated detector leading to an event rate of 7500 s^{-1} written on tape. Here, 3.5×10^9 $M_\gamma \geqslant 3$ coincidences were collected, yielding 17×10^9 unfolded triple coincidences. The high γ multiplicities in both reactions reduced the peak-to-total ratios, due to sum-up events and coincidences with unrestorable Compton scatter events. In both reactions the gain in peak intensity through the add-back of Compton scattered events was less than the increase in background intensity. Therefore, the analysis was performed without add-back, which reduced the full energy peak efficiency to $P_{\mathrm{Ph}} \approx 9\%$.

From the ^{68}Se experiment a level scheme could be derived only by analyzing triple data [see Fig. 1(a)]. In gated

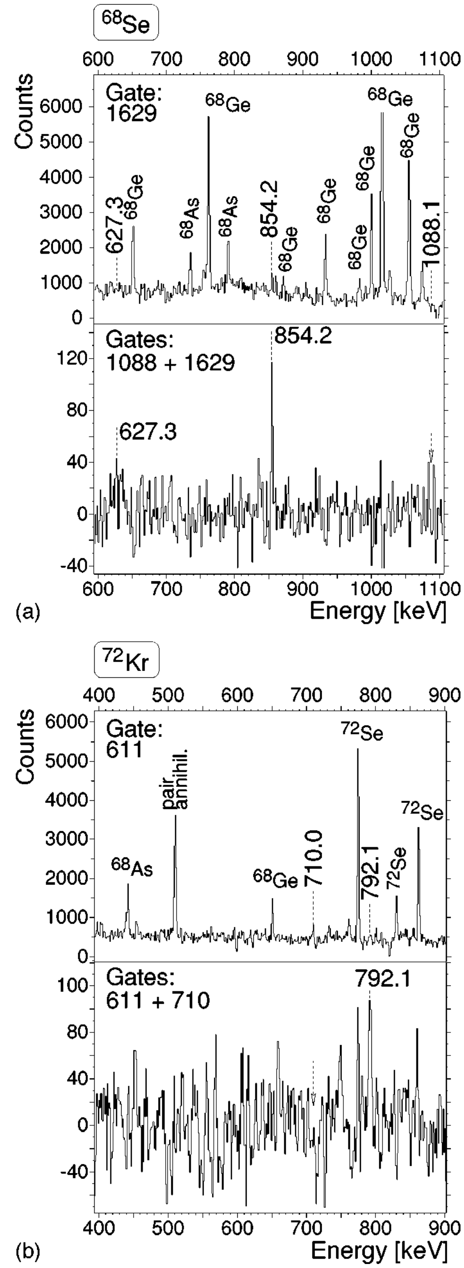

FIG. 1. Comparison of single gates (top) and double gates (bottom) for ^{68}Se (a) and ^{72}Kr (b).

spectra of a two dimensional matrix, the $2n$-channel ^{68}Se transitions could not be established because of the energy overlap with the mutually coincident 339, 344, and 854 keV transitions of the np-channel ^{68}As, which is the third strongest exit channel. Moreover, we discovered in ^{68}As new transitions of 1627 keV (not in coincidence with 854 keV) and in particular 1090 keV (in coincidence with 854 keV), making double gating of paramount importance for the analysis of ^{68}Se. Applying double gates, it turned out that the three transitions (343, 854, and 1088 keV) previously assigned to ^{68}Se [15] are not mutually coincident.

Although it could be ascertained that there is no coincidence between the 1088 and the 343 keV transition, the coincidence between the 854 and 343 keV transitions could neither be established nor excluded for ^{68}Se, because no further transition could be assigned to ^{68}Se in the spectrum

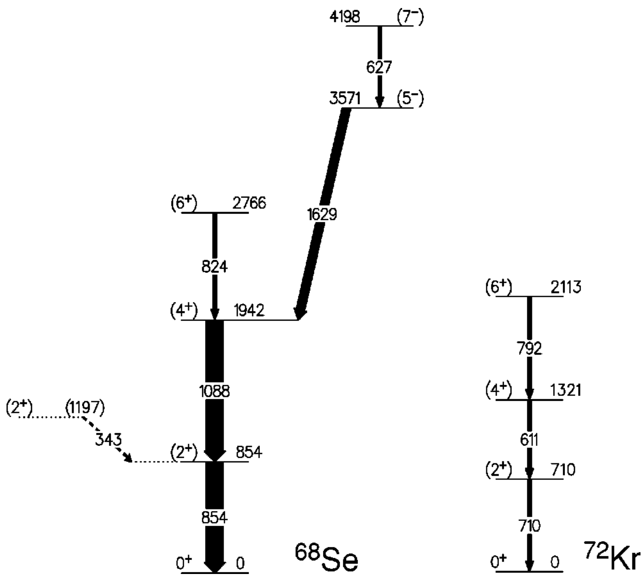

FIG. 2. Proposed level schemes of ^{68}Se (left) and ^{72}Kr (right).

gated doubly on the 854 and 343 keV lines. Thus, the 343 keV transition might feed the 854 keV state.

The level scheme of ^{68}Se shown in Fig. 2 was deduced from coincidences and intensities. The 854.2(3) keV transition was inferred as the ground-state transition, because in the recoil mass-spectrometer coincident spectrum [15] the 854 keV transition has the largest intensity. The relative intensities 100(17) of the 1088.1(9) keV transition (the 1088–1090 keV doublet being resolved) and 50(25) of the 1629.1(7) keV transition were determined in a spectrum gated on the 854 keV ground-state transition, while the relative intensities of the 627.3(6) keV transition, 20(11), and of the 823.9(8) keV transition, 18(11), were deduced in relation to the 1629 keV transition from a spectrum gated twofold on 854 and 1088 keV.

To compare the relative cross sections of ^{68}Se and ^{68}Ge, a gate was set on the strongest transitions populating the first excited state in either nucleus. From these spectra the intensities of the ground-state transitions in ^{68}Ge (308 000 events) and in ^{68}Se (230 events) were inferred, which yield a relation of 1 to 7×10^{-4}. We know from experience that for strong exit channels the measured relative cross sections are reproduced quite well by CASCADE calculations [27]. Hence, using the calculated ^{68}Ge cross section of 280 mb, a ^{68}Se cross section of $\sigma=200(50)$ μb was determined. This evaluated cross section accounts for 3×10^{-4} of the total cross section and is roughly in agreement with the CASCADE calculation in contrast to the cross section determined by Lister *et al.*, which was found to be five times smaller than anticipated [15]. The discrepancy might be due to a high spin isomer, leading to γ decays outside the focus of the Ge detectors in the recoil mass separator measurement. To discover such a high spin isomer, we performed a recoil shadow experiment by surrounding a thin target with a four-chambered NE213 neutron detector, while behind a 5-cm-thick Pb wall two Cluster detectors pointed at a stopper to detect isomeric γ decays of the deposited recoil nuclei. Nevertheless, we did not find a high spin isomer in ^{68}Se within an observational limit of 10 μb. Yet, with a lower detection limit at 1 ns, we found in the various reactions all the isomers expected from publications ($\tau=2$ ns–20 μs). In case of isomeric ground-state transitions, however, corroborating coincidences are not available. Therefore, an—although improbable—isomeric ^{68}Se ground-state transition of 343 or 854 keV cannot be excluded by this recoil shadow experiment because of the $E_x=2158$ keV isomer ($\tau=37$ ns) in ^{68}As, feeding states depopulated by the 854 and 344 keV transitions. For the reaction ^{32}S(115 MeV)+^{40}Ca, used in the recoil shadow experiment, which populates states with angular momenta up to 32 $\hbar$, the cross section of ^{68}Se was calculated by CASCADE to be as large as 1 mb. Thus, taking the observational limit of 10 μb into account, less than 1% of the ^{68}Se cross section is expected to proceed from a potential high spin isomer.

An evaluation of the ^{68}Se level spins could not be performed because of the low statistics. The ground state has the spin and parity 0^+ with a half-life of 35.5(7) s [28]. Spin and parity of the other states are suggested from the systematic of neighboring even-even nuclei. The transitions 854 and 1088 keV build the ground-state band up to probable spin 4^+. The feeding 824 keV transition might represent a backbending in the ground-state band in agreement with our cranking model calculations, which yielded a critical frequency of 0.5 MeV for aligning either $g_{9/2}$ protons and neutrons. Both the transitions 343 and 1629 keV are interpreted in analogy to ^{66,68}Ge and in particular the $N=Z$ nucleus ^{64}Ge. The possible 343 keV transition is interpreted as the decay out of the γ band, while the 1629 keV decay is interpreted as the $5^-\rightarrow4^+$ yrast transition. Also in the neighboring nuclei ^{70}Ge and ^{66,68}Zn [29] strong $E1$ transitions into the 4^+ state have been observed. Although $E1$ transitions are isospin-forbidden in a $T_z=0$ nucleus, it was shown that for ^{64}Ge the deduced $E1$ strength can be explained by an estimated 1.2% isospin mixing, indicating a Coulomb-mixing interaction strength comparable with that extracted from the β decay of ^{64}Ga [14]. As the isospin admixtures are expected to increase with mass, a strong $5^-\rightarrow4^+$ $E1$ transition would not be surprising for ^{68}Se. A lifetime measurement of the 3571 keV state would be very useful to quantify this point.

According to total Routhian surface (TRS) calculations using the Woods-Saxon cranking model [8], nuclei with large oblate deformation are centered around $N=Z=34$–36 [22]. In [15] it was argued that a rigid oblate deformation, as calculated in [22], would lead to an estimated 2^+ level of about 425 keV energy. The present TRS calculations for ^{68}Se (Fig. 3, bottom) show prolate-oblate shape coexistence with nearly degenerate minima at $\beta_2=0.23$, $\gamma=0°$, and $\beta_2=-0.26$, $\gamma=-60°$ for the ground-state. The potential barrier of about 300 keV could be further reduced if pn correlations would be included in the calculations. Even shape mixing might be possible, as predicted by microscopic model calculations for other nuclei in this mass region, e.g., ^{72}Kr [19]. The TRS at moderate rotation $\hbar\omega=0.4$ MeV shows a pronounced γ-soft triaxiality (Fig. 3 bottom), which might explain the diminished ratio $R=E(4_1^+)/E(2_1^+)=2.27$ [30] ($R=8/3=2.67$ for $\gamma=30°$ in the absence of rotation-vibration coupling [30]) as well as the possible 2_2^+ γ-bandhead state lying below the 4_1^+ level at 1197 keV [31]. The $\beta_2=0.33$—predicted by the present TRS calculation—compares well with a $|\beta_2|=0.28$ derived from $E(2_1^+)=854$ keV via Grodzins rule [16] if a triaxiality of $\gamma=25°$ is

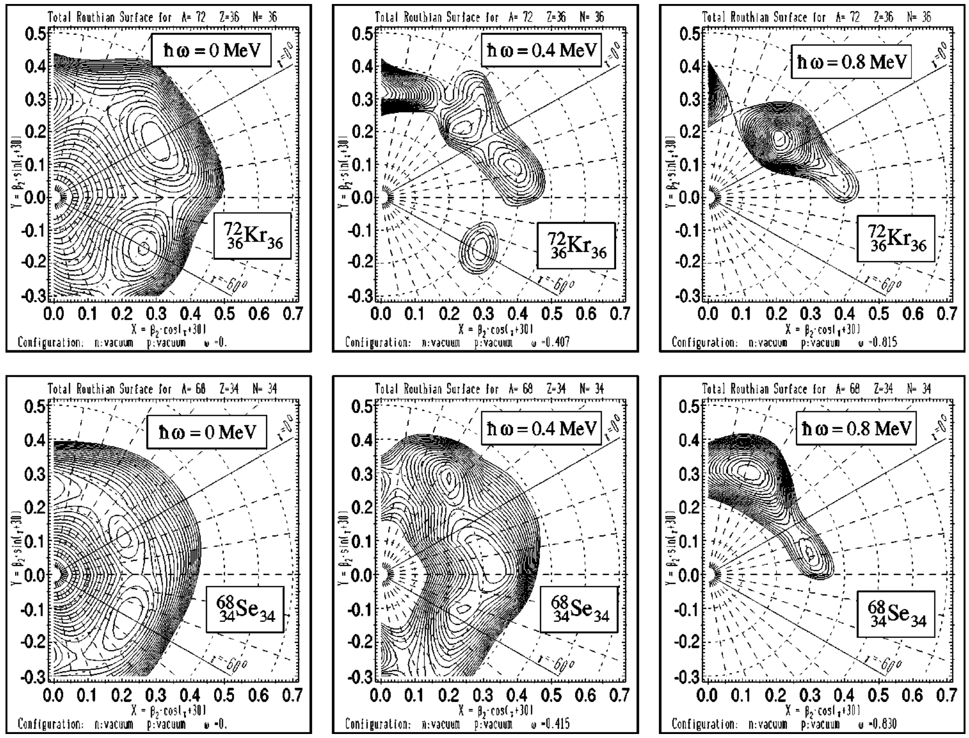

FIG. 3. TRS calculations for ^{72}Kr (top) and ^{68}Se (bottom). The separation between the contour lines is 0.1 MeV.

taken into account, which would yield $\beta_{eff}=0.84\beta$ [31]. At faster rotation $\hbar\omega=0.8$ MeV, a strong influence of the single particle states emerges, which might explain the 5^- and 7^- states by assuming a neutron or proton configuration $[g^1_{9/2}(p_{3/2}f_{5/2}p_{1/2})^1]$. Comparing ^{68}Se with ^{69}Se, the oblate deformation of the ^{69}Se $g_{9/2}$ band [4] appears to be generated and stabilized by the core-polarizing odd neutron. For a detailed interpretation of ^{68}Se, obviously further experimental data are needed, e.g., spins, parities, and lifetimes.

With the ^{72}Kr CLUSTER CUBE experiment only the mutual coincidences between the transitions 610.9(5), 710.0(5), and 792.1(6) keV could be established [see Fig. 1(b)] thus proving the first three excited levels of ^{72}Kr (see Fig. 2, right), which were proposed by [23] based on the transition intensities measured in coincidence with the recoil mass spectrometer. Recently, the level scheme of ^{72}Kr could be extended up to spin 16$\hbar$ by De Angelis *et al.* [32]. The newly assigned $8^+\rightarrow 6^+$ 995.6 keV transition already shows a large Doppler broadening of the line shape, which could explain our difficulties to extend the level scheme. The line shape analysis performed for the $8^+\rightarrow 6^+$ transition resulted in a quadrupole deformation $\beta_2=0.37(7)$ [32]. In accordance with [23,24,32] our ^{72}Kr data agree with expectations for the $N=Z=36$ nucleus based on prolate-oblate shape mixing inducing level repulsion in the low spin region, while at higher spins the nucleus is predicted to prefer prolate deformation (see Fig. 3, top, and [19]). Comparing the ^{72}Kr-transition intensities to the respective ^{72}Se ground-state band transition intensities, one obtains a relative intensity of 7×10^{-4} for ^{72}Kr. With a cross section of 145 mb for ^{72}Se, calculated by the fusion-evaporation code CASCADE [27], a cross section of 100(30) μb can be inferred for ^{72}Kr, representing 1.5×10^{-4} of the total cross section.

To summarize, the high efficiency of the CLUSTER CUBE setup allowed us to establish several excited states in the two $N=Z$ nuclei ^{68}Se and ^{72}Kr produced with a proportion of only 10^{-4} of the total fusion cross section. The level schemes are consistent with the systematics of the mass region. The sequence 710-611-792 keV in ^{72}Kr hints to prolate-oblate shape mixing and is quite different from levels schemes produced by strong prolate deformation in the $N=Z=38,40$ nuclei ^{76}Sr and ^{80}Zr. The proposed level scheme of ^{68}Se, with a $5^-\rightarrow 4^+$ $E1$ transition, resembles the moderately deformed γ-soft nuclei ^{64,66}Ge. Both nuclei, ^{68}Se as well as ^{72}Kr, appear to follow the predictions of the TRS calculations. In particular, the oblate or shape-coexistent deformations are *not* preserved if the nuclei start rotating.

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