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Allowed-unhindered β decay of ^{180}Yb and the nuclear structure of ^{180}Lu

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The β decay of mass-separated ^{180}Yb was investigated by measuring β-delayed γ rays and conversion electrons. Evidence was found for an allowed-unhindered β transition involving the transformation of a $7/2^-[514]$ neutron into a $9/2^-[514]$ proton. The experimental results include a new decay scheme of ^{180}Yb which gives evidence for a 5^+ ground state of ^{180}Lu and leads to the first identification of further low-spin configurations. These data are compared with predictions obtained from two-quasiparticle band-head energy calculations based on a zero-range residual interaction with appropriate Nilsson model wave functions.

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The odd-odd nucleus ^{180}Lu has attracted considerable interest during the last decade since its nuclear structure is closely related to the unsolved astrophysical puzzle of the solar abundance of ^{180}Ta^m. This isomer, at an excitation energy of 75 keV above the ^{180}Ta ground state [1,2], represents the rarest stable isotope of our solar system. The fact that it is shielded by stable nuclei from the nucleosynthesis paths of the s or r process leads to the still open question of the production mechanism. One major source for the nucleosynthesis of ^{180}Ta^m is believed to be the β decay of the $I^\pi=8^+$ isomer ^{180}Hf^m [3,4] which involves the ^{179}Hf(n,γ) neutron capture in an s-process scenario [5–7]. These contributions, however, do not exceed one third of the actual abundance of ^{180}Ta^m [8,9]. Therefore, it is of interest to search for additional post-r process production of the precursor ^{180}Hf^m. Conflicting results were reported for a β decay branch of ^{180}Lu to ^{180}Hf^m [3,10], which is apparently very small. An appealing idea for the solution of this puzzle is based on the possible β feeding of ^{180}Hf^m from a yet unobserved high-spin isomer in ^{180}Lu.

Some experimental and theoretical work has already been devoted to such a high-spin isomer. On the one hand, none of the experiments performed so far has detected a ^{180}Lu^m β decay. Presuming the existence of an isomer, only a half-life range of 1 to 10 sec can be deduced from the negative results [3,11]. On the other hand, detailed model calculations of the levels in ^{180}Lu have yielded insight into the structure of this odd-odd nucleus and allowed predictions for the existence and the properties of high-spin isomeric states as well as predictions of a 5^+ ground state of ^{180}Lu [12,13]. In particular, the identification of the β decay of ^{180}Lu to the 1608 keV 4^+ state in ^{180}Hf as an allowed, unhindered transition in a recent analysis [13] strongly supports the 5^+ assignment for the ^{180}Lu ground state. However, these predictions are still awaiting further experimental confirmation [4,14,15]. In 1987 the decay of the precursor ^{180}Yb, the heaviest known ytterbium isotope, was discovered but only limited information on the ^{180}Lu level structure could be deduced [14].

We report here on an experiment aimed to reinvestigate the β decay of ^{180}Yb to states in ^{180}Lu. Although only low-spin states are expected to be fed in this decay of an even-even nucleus, unambiguous level assignments are regarded as a key to the structure of ^{180}Lu, which is compared with recent calculations of the two-quasiparticle level energies.

The experiments were performed at the GSI on-line mass separator. Targets of natural tungsten or rhenium foils with a total thickness of 30–40 mg/cm^2 were irradiated with an 11 MeV/nucleon ^{197}Au or ^{136}Xe beam, provided by the UNILAC accelerator facility. The online mass separator was used to separate and collect the mass A=180 activities by means of a fast tape-transport system. The samples were periodically moved to the detector array. For some of the measurements two large-volume (70 % standard efficiency) Ge detectors and a 4π β counter were used. Alternatively, the detector array consisted of a low-energy Ge detector and a mini-orange electron spectrometer for the detection of conversion electrons in the range between 20 and 100 keV.

In order to suppress the strong γ-ray background from the 5.7-min ^{180}Lu ground-state decay, a hot FEBIAD-B2-C ion-source was mounted [16,17]. The catcher temperature was 2400 K. The suppression of ^{180}Lu reached a factor of 10^3 as compared to the thermal ion sources used in earlier experiments [4,10,14,18,19] while the release of ^{180}Yb was comparable. The intensity of the mass-separated ^{180}Yb beam was of the order of 1 atom per

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second. Hence the progress in the ion-source developments is regarded as a major advantage in these studies. The γ-ray spectrum displayed in Fig. 1 demonstrates that ^{180}Yb is a main activity besides ^{180}Lu, ^{180}Ir, and a contamination of molecular ions ^{164}Lu^{16}O^{+}. Gamma rays assigned to the decay of ^{180}Yb are compiled in Table I. The earlier reported transitions [14] were confirmed with the exception of the 548 keV line, this discrepancy being probably due to summing effects. In addition four new γ rays were identified. The mini-orange spectrometer allowed us to measure the conversion electrons of the 103, 109, and 120 keV transitions and their coincidence relations. An electron spectrum, taken in coincidence with the strong 173 and 339 keV γ transitions is shown as an inset in Fig. 1. This spectrum exhibits an unassigned electron line at about 34 keV energy.

The decay scheme of ^{180}Yb was constructed from the measured transition energies and intensities, from the deduced multipolarities of the low-energy transitions, and from the coincidence relations noted in Table I. Eight excited states of ^{180}Lu were identified and are shown in Fig. 2 together with the proposed spin-parity assignments. The strongest β branch of about 37% was the one populating the 982 keV state. Since mass formulas predict a Q_β value of $\sim$ 2 MeV for ^{180}Yb [20], this branch has a log *ft* value as low as 4.5, a unique signature for an allowed-unhindered β decay [21,22]. In this case, the underlying transition is unambiguously identified: One neutron of the coupled 7/2$^-$[514] pair of ^{180}Yb decays into a 9/2$^-$[514] proton while the other 7/2$^-$[514] neutron acts as a spectator. We can therefore assign the 982 keV state in ^{180}Lu to the 1$^+$ $\{9/2^-[514]_p-7/2^-[514]_n\}$ configuration.

Other configurations were deduced by coupling of the known odd proton and neutron quasiparticle states near their respective Fermi surfaces. An important outstanding question concerns the ground-state configuration of ^{180}Lu. Recent experiments [23] have shown that the

TABLE I. Energies E_γ, relative intensities $I_\gamma^{\rm rel}$, and measured coincidences of γ rays following the β decay of ^{180}Yb.

E_γ (keV)	$I_\gamma^{\rm rel}$	Coincident γ rays[a]
102.8	9(2)	120,339
108.8	8(2)	173,266
119.7	16(2)	103,339
172.9	100(5)	109,266,375,386,420
266.4	15(4)	109,173,386,420
339.4	47(6)	103,120,386,420
375.2	71(10)	173,386,420
385.8	41(10)[b]	103,109,173,266,339,375
419.6	52(8)	103,120,173,266,339,375
439.3	7(3)	
442.3	6(2)	

[a]Observed by setting a gate on the γ lines in the first column.
[b]Intensity corrected for a contribution of ^{180}Ir.

9/2$^-$[514]$_p$ state in ^{179}Lu occurs at a very low excitation energy of only 35 keV above the 7/2$^+$[404]$_p$ ground state, due to the increasing hexadecapole deformation in neutron-rich lutetium isotopes [4]. The 109th neutron, which forms the ground state of ^{179}Yb, occupies the 1/2$^-$[510] orbital. These states can couple to a 3$^-$ or a 5$^+$ ground state of ^{180}Lu [3,4,12–15]. With the almost degenerate 9/2$^-$[514] and 7/2$^+$[404] proton energies, ^{180}Lu may well be compared with its isotone ^{182}Ta. Here, the 5$^+$ state is at 16 keV above the 3$^-$ ground state and has a half-life of 0.3 sec [24].

In our experiment, two further 1$^+$ states of ^{180}Lu, namely those at 947 and 562 keV, were identified. For the 562 keV state, we propose the 1$^+$ $\{7/2^+[404]_p-9/2^+[624]_n\}$ configuration, based on the location of the 9/2$^+$[624] neutron configuration in ^{181}Hf [25]. The multipolarities of the 109 and 120 keV transition were deduced from the conversion electron data to be $M1$ (with a possible admixture of $E2$), and probably $E2$. If so, the levels at 442 and 453 keV have I^π=2$^+$ and

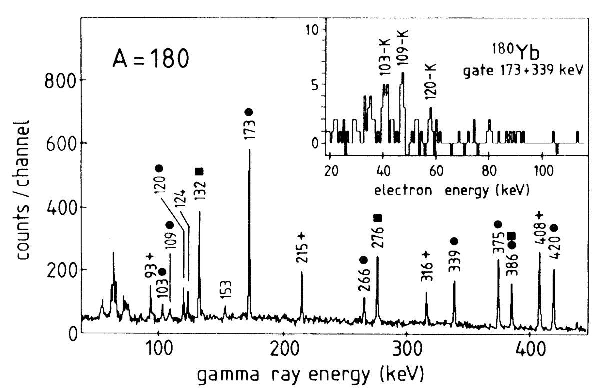

FIG. 1. Gamma-ray spectrum of A=180 activities measured in coincidence with signals from the 4π β counter. Observed γ rays were assigned to ^{180}Lu (crosses), ^{180}Ir (squares), ^{180}Yb (dots), and ^{164}Lu, the latter contaminant being due to the formation of ^{164}Lu^{16}O$^+$ ions. The inset shows conversion electrons measured with the mini-orange spectrometer in coincidence with the 173 and 339 keV transitions of ^{180}Yb decay.

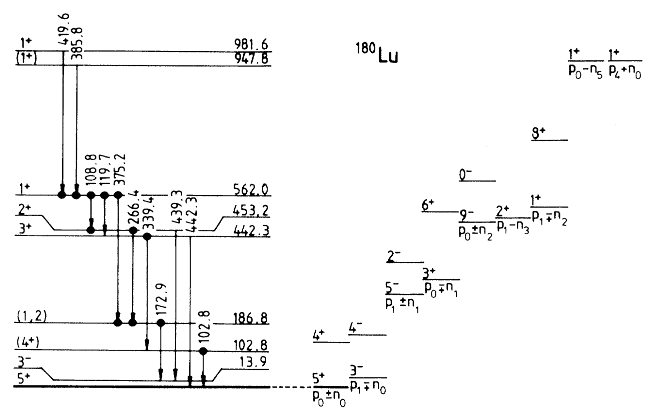

FIG. 2. Levels in ^{180}Lu and connecting γ transitions observed in the decay of ^{180}Yb (left), compared with the calculated two-quasiparticle spectrum (right). The following abbreviations have been used for the proton and neutron configurations: p_0 = 9/2$^-$[514], p_1 = 7/2$^+$[404], p_4 = 1/2$^-$[541], n_0 = 1/2$^-$[510], n_1 = 3/2$^-$[512], n_2 = 9/2$^+$[624], n_3 = 11/2$^+$[615], and n_5 = 7/2$^-$[514].

3^+. We have to assume that the 442 keV 3^+ state is the bandhead 3^+ $\{9/2^-[514]_p-3/2^-[512]_n\}$ since no other 3^+ states are expected at low energy in the two-quasiparticle spectrum of ^{180}Lu. A likely candidate for the 2^+ state at 442 keV is the 2^+ $\{7/2^+[404]_p-11/2^+[615]_n\}$ configuration. Based on these assignments, the ground state spin of ^{180}Lu can be deduced in the following way: As mentioned above, a 3^- and a 5^+ configuration are expected as the lowest-lying states in ^{180}Lu. The spin of the 186 keV level is ≤ 2 as a consequence of the strong 375 keV transition connecting this level and the 562 keV 1^+ state, presuming that no further 3^+ state is available. A 173 keV transition to a 5^+ state at 14 keV is hence unlikely and led us to assign the 5^+ configuration to the ground state and the 3^- configuration to the 14 keV state. One can expect that the connecting 14 keV $M2$ transition is isomeric and has a half-life of about one second.

In order to have a more quantitative description of the level structure of the odd-odd nucleus ^{180}Lu, theoretical calculations of the two-quasiparticle bandhead energies were performed. The two-quasiparticle spectrum is obtained by a superposition of the single-particle proton and neutron energies including the rotational energy correction and a contribution from the residual proton-neutron interaction energy. In deformed nuclei, the coupling of proton and neutron orbitals leads to a doublet of states with $K^{\pm} = (\Omega_p \pm \Omega_n)$. The relative ordering of the two members follows from the Gallagher-Moszkowski rule [26] favoring spin-spin coupling, and the energy difference of the two states is referred to as the Gallagher-Moszkowski splitting energy. Our calculations are based on a quantitative evaluation of the zero-range residual p-n interaction energy using the formulation described in detail in [27,28].

The two-quasiparticle spectrum obtained for ^{180}Lu is shown in Fig. 2 together with the experimental level scheme. The comparison gives excellent agreement and justifies the configuration assignments presented in this work. On the basis of these assignments, predictions for the existence of a high-spin isomer in ^{180}Lu can be made. In the calculated two-quasiparticle spectrum of ^{180}Lu, the most likely candidate for a high-spin isomer is the $9^-\{9/2^-[514]_p+9/2^+[624]_n\}$ configuration. This state is predicted above the $I^\pi K = 7^+5$ rotational state of the ground-state band. While the dominant decay mode of this level would probably be an internal $M2$, ΔK=4 transition, a weak β branch to ^{180}Hf^m is not yet excluded.

In conclusion, it appears that the stellar production mechanism of ^{180}Ta^m remains a puzzle. In addition to the problems involved with its r-process production, which was discussed in this paper, a further complication is related to the large photoabsorption cross section [29]. This fact, together with data from Coulomb excitation experiments [30], may indicate that ^{180}Ta^m is depopulated by (γ, γ') reactions in the (s process) stellar photon bath. Correspondingly, one may have to resort to other astrophysical scenarios, such as the recently proposed [31] process of inelastic neutrino scattering in a supernova, in order to understand the solar abundance of ^{180}Ta^m.

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