19 October 2000

PHYSICS LETTERS B

Physics Letters B 491 (2000) 225–231

www.elsevier.nl/locate/npe

Isomer spectroscopy of neutron rich $^{190}W_{116}$

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Received 19 April 2000; received in revised form 18 July 2000; accepted 11 September 2000
Editor: V. Metag

Abstract

Gamma-rays de-exciting a millisecond isomer in the neutron-rich nucleus $^{190}_{74}W_{116}$ have been observed following relativistic projectile fragmentation of a 1 GeV per nucleon ^{208}Pb beam. The isomeric decay populates the ground-state rotational band, with energies that indicate a significant deformation change at $Z = 74$ for the $N = 116$ isotones. The successful application of

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PII: S0370-2693(00)01051-0

the projectile fragmentation technique in a region of deformed nuclei opens up the prospect of exploiting K-isomer decays to probe the evolution of collective nuclear structure far from the valley of beta stability.

PACS: 25.70.Mn; 27.80.+w

A significant amount of information on the global behaviour of nuclei can be obtained from the energy spacing of the lowest lying states in even–even systems. For example, it is well established that the excitation energy of the first 2^+ state can be used to infer the extent of quadrupole deformation [1,2]. Similarly, the ratio of the excitation energies of the first 4^+ and 2^+ states can be used in a simple model [3], to distinguish between an axially symmetric deformed rotor (with an energy ratio of 3.33), a spherical, vibrational nucleus (2.0) and a triaxial rotor (~ 2.5). A number of attempts have been made to correlate this macroscopic nuclear behaviour with the valence numbers of protons and neutrons [4–7]. In general, for nuclei, where the spectroscopic information is available, the systematics follow smooth trends, providing sub-shell closures are taken into account [5–7].

The global properties of nuclei are tested by obtaining information on the low lying excitations of nuclei across as wide a range as possible. In practice, the heavy, neutron rich, rare earth nuclei are particularly difficult to access experimentally. These nuclei are inaccessible with stable beam/target fusion–evaporation reactions and are too heavy to be populated in fission. Although deep inelastic reactions have recently been used to access high spins in nuclei with a few neutrons more than the most neutron-rich stable isotopes [8], this technique is limited by a general difficulty in channel selection. Projectile fragmentation at intermediate and relativistic energies has proven to be an efficient and selective method of populating nuclei far from the valley of stability [9,10] and is an ideal tool for the study of high-spin metastable states in heavy neutron-rich nuclei [10].

Discrete γ-ray spectroscopy cannot be carried out at the production target in the case of exotic nuclei, since the intensity of the background is many orders of magnitude higher than that of the radiation emitted by the fragments of interest. However, these fragments can be transported and identified on an ion-by-ion basis. This method allows the study of the excited states only in those nuclei which are produced during the fragmentation in isomeric states, with lifetimes long enough to survive the time of transportation between the production target and the γ-ray detection system. The deformed rare-earth nuclei in the $A \sim 170$–190 region are well known for their so-called high-K isomeric states [11]. These isomers occur due to the maximal angular momentum coupling of a number of single nucleon orbitals with large angular momentum projections, Ω, on the nuclear symmetry axis. Such high-K ($K = \sum_i \Omega_i$) intrinsic states are often hindered in their decay to the low-K rotational states since this involves a large alteration in the total angular momentum orientation, which is forbidden via low multipolarity transitions if the K projection is a good quantum number. This region of K-isomerism in the rare earth nuclei has long been predicted to extend into the neutron-rich Hf/W/Os region with $A \sim 180$–200 [12,13]. However, until now, the spectroscopic information available on such neutron-rich nuclei has been severely limited due to the difficulty in synthesising these systems at the medium to high spins required to populate such states.

This letter reports on our discovery of a high-spin isomeric decay in the neutron-rich nucleus $^{190}\mathrm{W}_{116}$, populated following a relativistic projectile fragmentation reaction. The isomer is interpreted as decaying into the ground-state band with energy spacings that suggest a significant deformation change. This isotope is four mass units heavier than the most neutron-rich stable tungsten isotope and has eight neutrons more than the heaviest tungsten isotope which can be measured at high spins with fusion–evaporation reactions using stable beam/target combinations [14]. ^{190}W was the heaviest isotope of this element which had been experimentally synthesised in $(\mathrm{n, n2p})$ and $(\mathrm{p, 3p})$ reactions, although no excited states had been observed [15].

In order to investigate isomeric states in neutron-rich nuclei in the Hf/W/Os region, a beryllium target of thickness 1.6 g/cm^2 was bombarded with a 1

GeV/nucleon, ^{208}Pb beam provided by the SIS accelerator in GSI. The typical, on-target beam intensity was 2×10^8 lead ions per 12 second beam spill. The nuclei of interest were separated and identified using the FRagment Separator (FRS) [16] operated in standard achromatic mode. An additional degree of selectivity for the ions reaching the final focus of the FRS was achieved by placing a wedge-shaped aluminium degrader in the intermediate focal plane of the separator. Niobium foils of thickness 221 mg/cm^2 were placed after both the target and the degrader in order to maximise the electron stripping. Typically 90% of the ions of a given isotope were fully stripped. The mass-to-charge ratio of the ions, A/Q, was determined from their time of flight in the second part of the FRS. The measured change of the magnetic rigidity of ions before and after they passed through this degrader was used to obtain unambiguous charge identification. The energy deposition of the identified fragments was measured as they passed through a gas ionisation chamber. Following this, they were slowed down in a variable thickness aluminium degrader and finally stopped in a 4 mm thick aluminium catcher. The atomic number of the ions was determined using three methods: (i) by measuring how the position of the nuclei in the final focal plane varies with A/Q; (ii) from their energy loss in the ionisation chamber; and (iii) from the emitted X-rays following internal conversion decays of states below isomers. The identification procedure is described in more detail in Ref. [17].

The total transmitted ion rate was kept below 1 kHz in order to minimise dead-time losses. Scintillator detectors were placed both in front of and behind the catcher, allowing the offline suppression of those fragments destroyed in the slowing down process or those which were not stopped in the catcher (totaling $\approx 20\%$). The catcher was surrounded by four clover-style germanium detectors. The photopeak γ-ray efficiency of this array was measured to be 8% at 661 keV. The effective detection efficiency was however reduced in practice due to the ions stopping in the catcher, which gave rise to a prompt burst of low energy X-rays and bremsstrahlung. This had the effect of “blinding” on average 10 of the total 16 detector elements in each event.

At the catcher, the prompt and delayed γ-rays in coincidence with the individually identified fragment were recorded. The time difference was measured between the implantation of the fragment in the stopper (as measured by the time signal from a plastic scintillator placed in front of the stopper) and a subsequently detected γ-ray in the array, over ranges of 8 μs and 80 μs. Since the time of flight through the FRS was approximately 300 ns, this setup allowed the detection of isomeric decays with half-lives in the typical range of 100 ns to several hundred microseconds. Note, however, that shorter lifetimes could also be detected if the decay branch by electron conversion was hindered for specific charge states of the ion [9]. This technique is not suitable for investigation of β-decay in this mass region, where half-lives of seconds or more are anticipated.

The results on ^{190}W were obtained from two different magnetic rigidity settings. Approximately 85% of the data come from a setting optimised to select fully stripped nuclei centred on the maximal transmission of ^{191}W, while the remaining 15% of the data come from a second setting, centred on the nucleus ^{184}Lu. In this latter case, the hydrogen-like ^{190}W ions (those containing a single atomic electron) were simultaneously transmitted through the FRS. A total of 4.5×10^4 ^{190}W ions were collected with an average transmission rate of 0.2 ions/s. The identification plot for the setting optimised to select the fully stripped nuclei around ^{191}W is presented in Fig. 1. The detection of the previously identified γ rays following the de-excitation of the $I^\pi = 7^-$ $\tau = 20$ ns isomer in ^{200}Pt [18] was used to confirm the calibration of the particle identification. This isomer provides a clear, internal calibration for both A/Q and Z values using the time of flight and energy loss in the ionisation chamber, respectively.

The γ-ray spectrum observed in delayed coincidence with ^{190}W ions is shown in Fig. 2. The weak population of this exotic nucleus negates the use of γ–γ data to prove the coincidence relationships between these transitions. Within experimental errors, the γ-rays at 207, 357, 485, 591 and 695 keV have the same intensity when corrected for detection efficiency. The systematics of this deformed region strongly suggest that they form a rotational cascade (i.e., they have E2 character), built on the ground state of ^{190}W (see Fig. 3). As Fig. 3 shows, the energies of the assumed rotational cascade in ^{190}W appear to be consistent with a reduction in collectivity compared to the lighter isotopes. The low energy part of the spectrum shown in Fig. 2 shows the tungsten X-rays and a 46 keV γ-

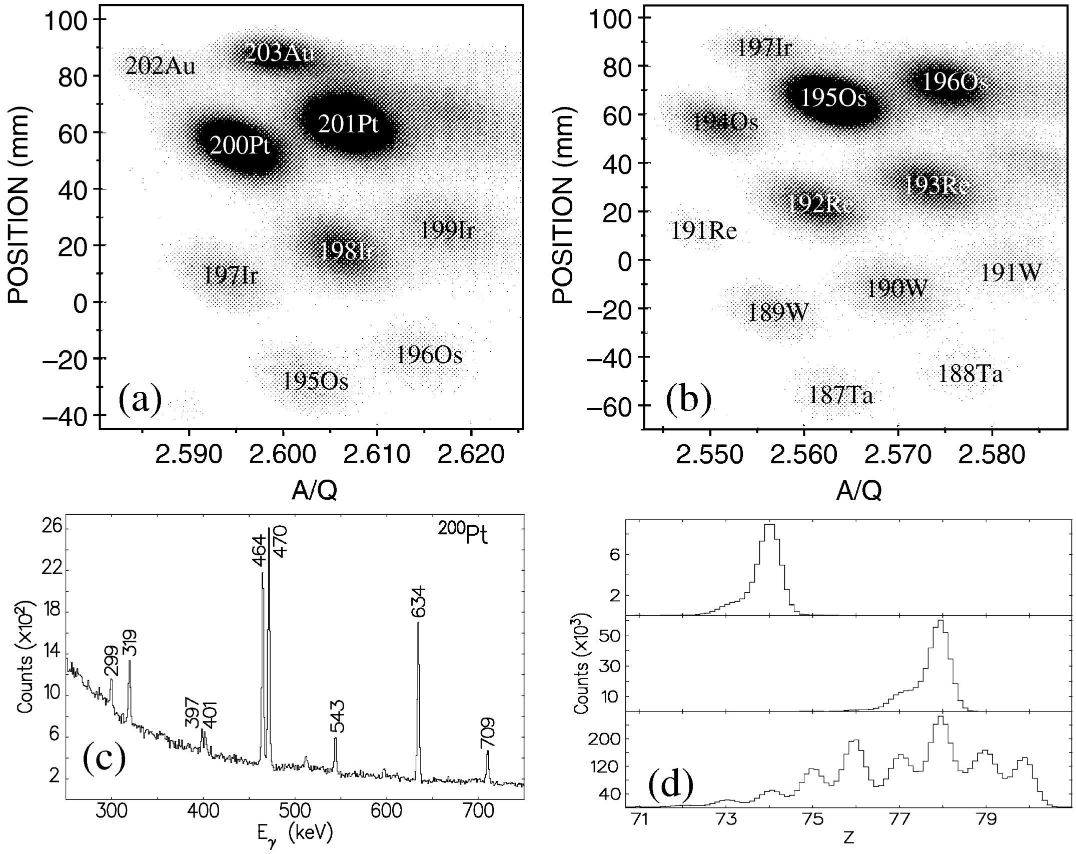

Fig. 1. Identification plot of the fragments by the FRS for (a) hydrogen like ions ($Q = Z - 1$) and (b) fully stripped ions ($Q = Z$) for the setting centred on fully stripped ^{191}W. Panel (c) shows the gamma-spectrum recorded in coincidence with the events labelled as '200Pt' in (a). All the indicated γ-ray transitions belong to ^{200}Pt. The strongest transitions were already known [18]; the others were found in the present experiment and proved to belong to ^{200}Pt by γ–γ coincidence measurement. (d) Z spectra obtained from the ionization chamber. From below: total Z spectrum, events corresponding to '200Pt' in (a), and events corresponding to '190W' in (b). As the latter two spectra show, there is a small contamination from nuclei with $Z - 1$, namely $^{A-5}_{Z-1}$X [10], which can be removed by gating on the ionisation chamber.

ray transition. Assuming that the 46 keV transition is the direct decay out of the isomer, it can be assigned on the basis of its internal conversion coefficient ($\alpha_{\text{exp}}(46\ \text{keV}) < 1.0$, $\alpha_{\text{th}}(46\ \text{keV},\ \text{E1}) = 0.6$) as an E1 transition, as all the other multipolarities have values much higher than unity at this energy. (We attribute approximately one third of the 58 keV X-ray peak to electron conversion associated with the delayed E2 transitions, and the rest appears to be associated with prompt contaminations.) The background of the spectrum presented in Fig. 2 is associated with the room background ($\sim$ 50%) and the prompt contamination ($\sim$ 50%).

The mean lifetime for the isomeric state was determined to be in the range between 135 µs and 4.5 ms. The time distribution of the γ-ray transitions identified in ^{190}W is shown in the inset of Fig. 2. The lifetime is clearly longer than the 80 µs range of the Time-to-Amplitude Converter (TAC). By taking the ratio of counts in the first and last third of the 80 µs time window, an estimate of the mean lifetime for the isomer of $\tau = 390^{+\infty}_{-255}$ µs was obtained. This lifetime was obtained for the gamma-ray transitions with the background subtracted, therefore it is excluded that the long lifetime is related to the decays of long-lived activities accumulated in the catcher. An upper limit of

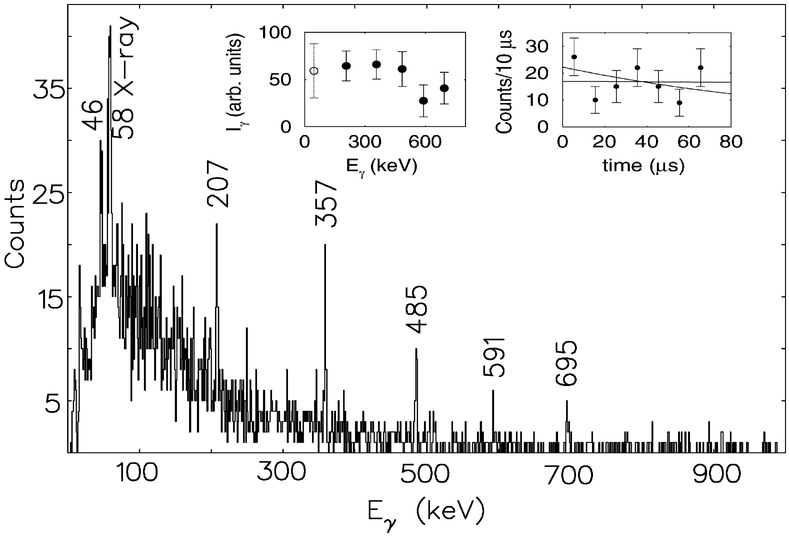

Fig. 2. Delayed γ-ray spectrum for ^{190}W with the condition that the γ-rays were detected between 1 and 70 μs after the ion implantation. The dispersion on the X-axis is 1 keV per channel. The insets show the relative intensities and the summed time spectrum associated with the labelled γ-ray transitions. The two lines on the time spectrum correspond to the upper and lower limits for the lifetime of $\tau = 4.5$ ms and $\tau = 135$ μs, respectively.

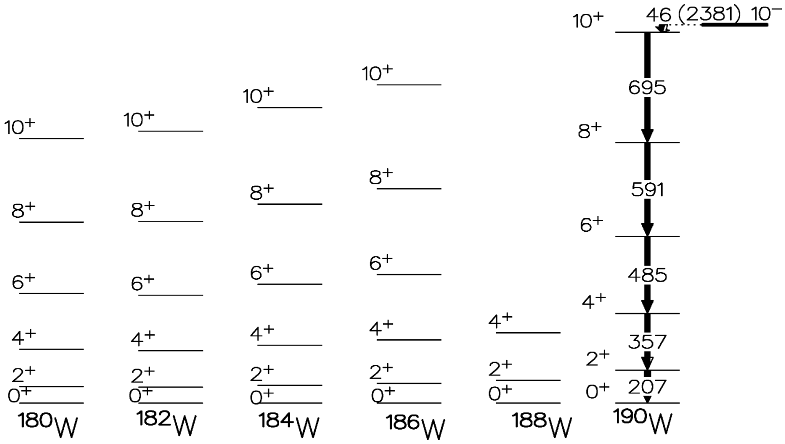

Fig. 3. Proposed decay scheme for ^{190}W as obtained from the present work, with the systematics of the yrast band energies of the even–even tungsten isotopes from mass 180 upto 188.

4.5 ms for the mean lifetime can be obtained from the absolute γ-ray intensities, supposing that all the ^{190}W nuclei are produced in the isomeric state.

Assuming that the observed 207 keV transition represents the yrast $2^+ \to 0^+$ decay, the Grodzins empirical estimate [1] for the ground-state deformation of ^{190}W yields a value of $\beta_2 = 0.17$. Fig. 4(a) shows the results of deformed Woods–Saxon–Strutinsky potential-energy-surface calculations for ^{190}W (as described in [19]) which predict a ground-state deformation of $\beta_2 = 0.17$ ($\beta_4 = -0.06$ and $\gamma = 0°$), remarkably consistent with that obtained from the Grodzins estimate. The calculations also predict a shallow nature to this minimum with respect to the triaxial de-

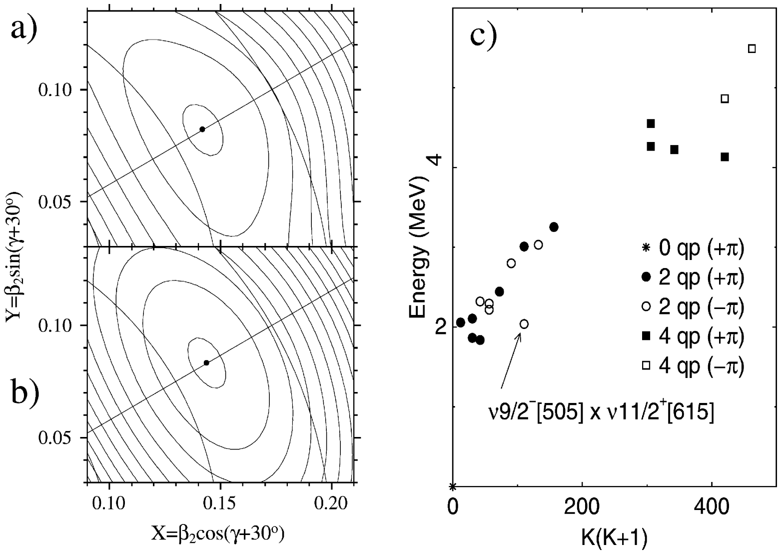

Fig. 4. Potential energy surface calculations for (a) the ground-state configuration and (b) the $K^\pi = 10^-$ configuration for ^{190}W. The energy difference between two successive contour lines is 200 keV. (c) Blocked BCS calculations for ^{190}W, showing the favoured nature of the $K^\pi = 10^-$ two quasineutron configuration.

gree of freedom, which is discussed below. In order to assign a single particle configuration to the isomeric state, blocked-BCS (Bardeen–Cooper–Schrieffer) calculations as described in reference [13] were performed for ^{190}W, using the same deformation parameters as obtained from the deformed Woods–Saxon–Strutinsky calculations. The quasiparticle energies and the pairing force strengths were fitted to known states of the neighbouring ^{190,191,192}Os and ^{191}Re nuclei (consistent with extrapolation from Ref. [20]). As shown in Fig. 4, there is predicted to be a low-lying two-quasiparticle state with a two-quasineutron $K^\pi = 10^-$, $9/2^-[505] \otimes 11/2^+[615]$ Nilsson configuration. Configuration-constrained potential-energy-surface calculations [21] have been performed for this $K^\pi = 10^-$ state. The results, shown in Fig. 4, predict almost identical shapes for the isomeric and the ground state, justifying the usage of these deformation parameters in the blocked-BCS calculation. Therefore, we suggest a $K^\pi = 10^-$, $\nu 9/2^-[505] \otimes 11/2^+[615]$ configuration for the observed isomer. An isomer with the same proposed structure has been observed in the $N = 116$ isotone ^{192}Os$_{116}$ [22].

The heavier $N = 116$ isotones, i.e., ^{192}Os and ^{194}Pt, are well known examples of γ-soft nuclei [23]. Therefore it is expected that the γ-degree of freedom plays an important role also in ^{190}W. The deduced ratio of the energies of the 4^+ and 2^+ states of 2.72 is close to the asymptotic limit of 2.5 for a γ-soft nucleus [3,4]. This interpretation is consistent with the potential energy surface calculations shown in Fig. 4, which suggest a significant γ-softness.

The implied γ-softness in ^{190}W is consistent with the lifetime for the decay out of the isomer. The reduced hindrance is defined as $f = (\tau^\gamma/\tau^W)^{1/(\Delta K-\lambda)}$, where τ^γ is the partial γ-ray mean-life, τ^W is the Weisskopf single-particle estimate and λ is the transition multipolarity. For the $K^\pi = (10^-)$ isomer in ^{190}W, assuming an E1, $\Delta K = 10$ decay with mean lifetime limits between 135 μs and 4.5 ms, results in a reduced hindrance, f, of between 6 and 10. This corresponds to a much enhanced E1 decay compared to the values for the sequence of $K = 8^-$ states in this region [24], which all have f-values of greater than 30. The small f-value for ^{190}W indicates a significant reduction in the purity of the K quantum number for either the yrast band and/or the isomeric state, which may be ascribed to the γ-softness. (Note that an E1-hindrance comparison with the isotone ^{192}Os is not possible since, in that case, the $K^\pi = 10^-$ isomer lies

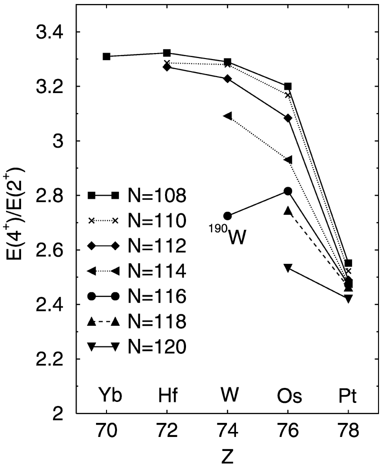

Fig. 5. Systematics of the ratio of the first 4^+ and 2^+ level energies in heavy rare earth nuclei.

lower in energy than the 10^+ member of the ground-state band.)

While the general feature of γ-softness is according to expectations in this mass region, a closer examination of the $4^+/2^+$ energy ratios is revealing, as shown in Fig. 5. The new data point for $^{190}W_{116}$ as deduced from the current work shows a striking deviation from the pattern for the lighter isotonic chains, which asymptote to the rotational limit value of 3.33 with decreasing proton number. Although the energies of the first two excited states of ^{190}W can be explained in terms of triaxiality, their ratio compared to the systematics is not fully understood. The clear bifurcation in this plot, arising from the new data point, is reminiscent of the systematics representing the breakdown of the $Z = 64$ shell gap for $N < 78$ and $N > 88$ [4, 6]. Mach [7] has discussed the alteration of effective shell gaps in this neutron rich region and proposed the possibility of a sub-shell gap for proton number 76. More data on the ground-state bands of neutron rich even–even nuclei in this region are clearly required to address this question fully. The ^{190}W data point suggests this may be fertile ground for future spectroscopic studies.

In conclusion, the yrast sequence of the neutron rich isotope, ^{190}W, has been deduced following the decay of a proposed $K^\pi = (10^-)$ isomer, populated in the fragmentation of a relativistic energy ^{208}Pb beam. The excitation energies of the first two excited states suggest a deformation effect. The present results open up the prospect of exploiting K-isomer decays to study the structure of nuclei inaccessible so far.

The excellent work of the technical and accelerator staff at GSI is acknowledged. This work is supported by EPSRC(UK), Polish Committee of Scientific Research under grant KBN 2 P03B 036 15, Department of Energy contract DE-FG02-96ER40983 (USA), and the EU Access to Large Scale Facilities Programme. The array of segmented Clover Ge detectors is jointly funded by CEA (France), EPSRC (UK), GSI (Germany) and NBI (Denmark).

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