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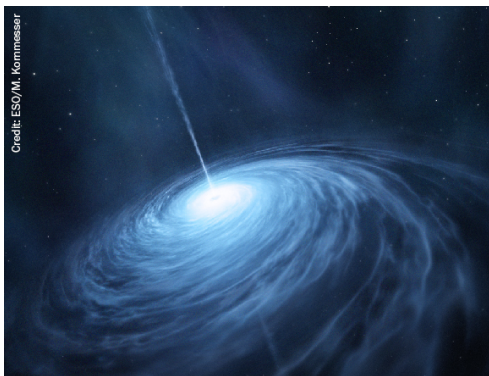
Mass measurement of Re-190

M R Griffiths[1,4] , **C Wheldon**[1] , **Tz Kokalova**[1], **A Turner**[1],
S Pirrie[1], **V Ziman**[1], **N I Ashwood**[1], **J D Malcolm**[1], **M Barr**[1],
M Freer[1] , **Th Faestermann**[2] , **H-F Wirth**[3], **R Hertenberger**[3],
R Gernhäuser[2] **and R Krücken**[2]

[1] School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT, United Kingdom
[2] Physik Department, Technische Universität München, D-85748 Garching, Germany
[3] Fakultät für Physik, Ludwig-Maximilians-Universität München, D-85748 Garching, Germany

E-mail: m.r.griffiths@pgr.bham.ac.uk

Abstract

In this paper, a measurement of the atomic mass and mass excess of $^{190}_{75}$Re are presented. This isotope and $^{192}_{77}$Ir were produced at the Maier-Leibnitz Laboratory (MLL) in Munich in the ^{192}Os$(d, \alpha)^{190}$Re and ^{194}Pt$(d, \alpha)^{192}$Ir reactions. The Q3D magnetic spectrograph was used to measure the momenta of the α-particle ejectiles in order to reconstruct states in both ^{190}Re and ^{192}Ir. A mass calibration was performed using known energy levels in ^{192}Ir. These measurements were used to obtain a new value of the mass excess of ^{190}Re, -35583 ± 5 keV. The previously known literature value is -35640 ± 70 keV.

Keywords: $^{190}_{75}$Re atomic mass, $^{190}_{75}$Re mass excess, nuclear reaction ^{192}Os$(d, \alpha)^{190}$Re, Q3D magnetic spectrograph

(Some figures may appear in colour only in the online journal)

1. Introduction

The neutron-rich isotope $^{190}_{75}$Re$_{115}$ lies on the decay path of nuclei populated in the astrophysical rapid neutron capture process (the *r*-process). Additionally, the mass $\approx$170–190 region of the nuclide chart is known for the occurrence of large numbers of metastable (isomeric) nuclear states caused by significant quadrupole deformations [1]. These *K*-isomers (so called due to

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[4]Author to whom any correspondence should be addressed.

the large angular momentum projection, K, on the nuclear deformation axis) are deformation aligned states and experience hindered decays to the rotationally aligned nuclear ground state structures. The long lifetimes of some of these levels can form astrophysical waiting points at low excitation energies [2].

Rhenium-190 exhibits an isomeric state with $I^\pi = (6^-)$, $t_{1/2} = 3.2 \pm 0.2$ h, observed at 204 ± 10 keV by Reed *et al* [3] at the Experimental Storage Ring (ESR) at GSI in Darmstadt. The ^{190}Re ground state has $I^\pi = (2^-)$ and $t_{1/2} = 3.1 \pm 0.3$ min [4]. However, not only is there significant uncertainty in the excitation energy of the excited state, but the atomic mass of ^{190}Re is further uncertain by ± 70 keV [5]. Schatz [6] has pointed out the importance of determining masses to better than 10 keV for understanding astrophysical processes, as it means uncertainties in the mass do not dominate over reaction-rate uncertainties (reference [6] is focused on the *rp*-process, but this condition has also been shown to apply to other astrophysical processes, such as the *r*-process [7]). This allows production mechanisms to be more easily investigated. This paper details an experiment that has been performed to accurately measure the mass of ^{190}Re.

2. Experimental method

The experiment was performed using the Q3D magnetic spectrograph [8, 9] at the Maier-Leibnitz Laboratory (MLL) in Munich where ^{190}Re and ^{192}Ir, the latter an isotope with precise literature values for its mass and energy levels [5, 10, 11], were produced. This was done by bombarding targets of ^{192}Os and ^{194}Pt with an 18 MeV deuteron beam to induce the ^{192}Os$(d, \alpha)^{190}$Re and ^{194}Pt$(d, \alpha)^{192}$Ir reactions. The targets had thicknesses of 45 μg cm^{-2} (^{192}Os) and 66 μg cm^{-2} (^{194}Pt) and both were backed with 7 μg cm^{-2} of carbon. The beam was produced using the 14 MV tandem Van de Graaff accelerator at MLL with beam currents between 0.4 μA and 1.35 μA. The Q3D spectrograph was positioned at an angle of 20° to the beam axis in the horizontal plane and used to measure the energy of α-particle ejectiles, from which the energy of the recoiling binary partner nuclei could be inferred. The magnetic optical properties of the Q3D are such that the particles corresponding to a given excitation energy are focused to the same point on the focal plane, independent of angle. Therefore, position on the focal plane corresponds to excitation energy of the unobserved recoil particle. For this experiment, the Q3D was set so that excitation energy in ^{190}Re, $E_x^{\text{Q3D}} = 400$ keV, was focused on the focal plane with an acceptance range of approximately -300–600 keV to ensure the low-lying states in ^{192}Ir were detectable using approximately the same magnetic field settings. The magnetic fields of the Q3D were set for the ^{192}Os$(d, \alpha)^{190}$Re reaction throughout the whole experiment.

3. Results

The resonance peaks in the energy spectra of ^{190}Re and ^{192}Ir have been fitted with Gaussian functions, as shown in figure 1. Due to properties of the Q3D the low energy peaks in ^{190}Re are skewed and therefore these peaks have been fitted as skewed Gaussian functions. Higher energy peaks in the ^{190}Re spectrum have also been identified, but are not the focus of this work. Due to the high level density in some regions of the ^{192}Ir spectrum, it was not possible to assign exact energies to all of the peaks as they contain contributions from multiple resonance components that could not be deconvolved. Such peaks do not contribute to the calibration and their fitted energies are shown in brackets in figure 1. The peak widths of about 10 keV full width at half maximum (FWHM) are dominated by experimental resolution, the most significant contribution to which are the energy-loss differences of α-particle ejectiles due to the target thickness. The difference in the ejectile energy corresponding to the ground states
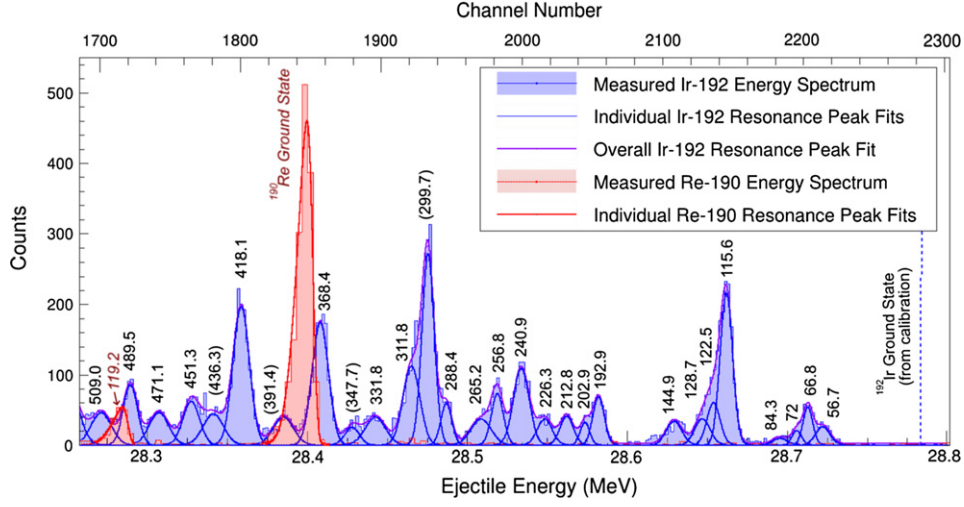
Figure 1. Fitted low energy region of the ^{192}Ir energy spectrum, with the excitation energies of peaks used in the calibration labelled in keV and those omitted due to comprising of multiple close-lying resonances labelled in brackets [11, 13]. The plot shows both the ejectile (α-particle) energy and the corresponding channel number for the focal plane detector on the x-axes. Here, a higher value of channel number corresponds to a lower excitation energy since ejectile energy is being measured. The fitted ground-state and first excited-state peaks in ^{190}Re have been overlaid and labelled in red. The ground-state position of ^{192}Ir (found using the calibration) is also indicated, but was not populated due to its $I^\pi = 4^+$ configuration being incompatible with the ^{194}Pt target ground-state configuration.

was added to the difference in recoil energy between the two nuclei to give the difference between the Q-values of the reactions used to produce the two nuclei. Using this value, along with known mass excesses [5] for all other isotopes involved in the reactions, a value for the mass excess of ^{190}Re can be found as

$$\Delta M_{\mathrm{Re}} = \Delta Q_{\mathrm{Ir-Re}} - \Delta M_{\mathrm{Pt}} + \Delta M_{\mathrm{Os}} + \Delta M_{\mathrm{Ir}}. \tag{1}$$

Here, ΔM_{Re}, ΔM_{Pt}, ΔM_{Os} and ΔM_{Ir}, represent the mass excesses of ^{190}Re, ^{194}Pt, ^{192}Os and ^{192}Ir, respectively, with ΔQ representing the difference in Q-value between the ^{192}Ir and ^{190}Re reactions. This is the difference in energy between the α-particle ejectiles corresponding to the respective ground states, shown in figure 1, added to the difference between the recoil energy of ^{192}Ir and ^{190}Re. Defining the position of the ^{192}Ir ground state to correspond to an excitation energy of 0 keV gives the position of the ^{190}Re ground state peak as 373 ± 4 keV. Through non-relativistic two-body kinematic calculations, the difference in recoil energy between the ^{192}Ir and ^{190}Re nuclei was found to be 2.1 keV with negligible error compared to the uncertainty in the difference between ground state energies. Therefore, the difference in Q-value between the two reactions was found to be $\Delta Q_{\mathrm{Ir-Re}} = 375 \pm 4$ keV overall. This Q-value difference was then used to calculate information such as the binding energy per nucleon and the atomic mass of ^{190}Re. The values for the parameters used in equation (1) are shown in table 1.

In figure 1, the first excited state in ^{190}Re can also be seen. The fitted energy of this state is found to be 119.2 ± 0.7 keV, compared to the current literature value of 119.12 ± 0.05 [4]. Another noteworthy state is the low lying $I^\pi = 1^-$, 56.72 keV energy level in ^{192}Ir. This corresponds to the well studied ^{192m1}Ir isomeric state [12].

Table 1. Values used to calculate the mass excess of ^{190}Re using equation (1). The value for $\Delta Q_{\text{Ir-Re}}$ was found in this experiment, with the mass excess values taken from literature [5].

$\Delta Q_{\text{Ir-Re}}$ (keV)	ΔM_{Pt} (keV)	ΔM_{Os} (keV)	ΔM_{Ir} (keV)
375 ± 4	-34760.1 ± 0.5	-35882.2 ± 2.3	-34835.6 ± 1.3

Table 2. Properties of ^{190}Re measured in this experiment compared to known literature values [5].

	Mass excess (keV)	Atomic mass (keV)	Atomic mass (μu)	Binding energy per nucleon (keV)
Current work	$-35\,583 \pm 5$	$176\,948\,297 \pm 5$	$189\,961\,800 \pm 5$	7949.78 ± 0.03
Literature	$-35\,640 \pm 70$	$176\,948\,240 \pm 70$	$189\,961\,740 \pm 80$	7950.1 ± 0.4

In table 2 the results of this experiment are shown alongside the previously known literature values. It is clear that the newly obtained quantities all lie within the error bars of the previous values suggesting that there is good agreement between the two sets of results. It is also evident that the uncertainty has been reduced greatly and is now an order of magnitude lower compared to previous values. This is not only true for the measurement of the mass excess but also, by definition, for the atomic mass and binding energy per nucleon.

3.1. Uncertainty

The uncertainties on the mass excesses of the other nuclei used in this experiment, ^{192}Ir, ^{192}Os and ^{194}Pt, are 1.3 keV, 2.3 keV and 0.5 keV, respectively [5]. As can be seen in equation (1), the uncertainty on the ^{190}Re mass excess depends on these three values, with the larger uncertainty for ^{192}Os being most significant. Errors also arise due to the manner in which the difference in Q-value is found. In the experiment the ground state in ^{192}Ir was not populated and, as the mass measurement relies on knowing the difference in measured energy between the ground states in ^{192}Ir and ^{190}Re, the ^{192}Ir ground state was found by extrapolating the calibration beyond the peaks used to produce the calibration itself, as the ^{192}Ir ground state lies at a higher channel number than any peak observed in this experiment. An alternative method, which does not involve extrapolation, is to find the difference in energy between the first excited state in ^{192}Ir, the $^{192\text{m}1}$Ir isomeric state at 56.72 ± 0.01 keV [12], and the ^{190}Re ground-state. However, due to the introduction of the uncertainty on the energy of this state and the fitted centroid value of the corresponding peak, this method does not lead to an overall reduction in uncertainty. The extrapolation introduces uncertainty in the position of the ^{192}Ir ground state which is then propagated into the uncertainty in the difference in Q-value between the reactions.

The calibration was performed using ^{192}Ir as it behaves in a similar manner to ^{190}Re in the Q3D spectrograph due to the two nuclei having similar nucleon numbers and their ability to be produced in the same (d, α) reaction. However, the ^{192}Ir level scheme is complex with high level density in some regions, as seen in figure 1. This, along with relatively low statistics, means the ^{192}Ir spectrum is not ideal for performing a calibration and therefore uncertainty is introduced by the calibration as the peaks used to produce the calibration often have significant uncertainty in their centroid position. This uncertainty is then transferred to the calibration in the form of upper and lower bounds for energy values found using the calibration. Additionally, the fit of the ^{190}Re ground state yields a centroid value with an associated uncertainty. Both of

these factors contribute to the uncertainty in the Q-value difference between the two reactions, which is found to be 375 ± 4 keV as stated above. Therefore, the dominant uncertainties in this experiment are the error in the difference between the Q-values and the error in the mass excess of ^{192}Os.

As previously mentioned, the uncertainty in the calculation of the mass excess of ^{190}Re depends on known uncertainties in the values of the mass excesses of ^{192}Os, ^{192}Ir and ^{194}Pt as well as experimental uncertainties. Therefore, the uncertainty in the mass excess measurement of ^{190}Re measured here is larger, but of the same order of magnitude, compared to other nuclei that lie in the same mass region as ^{190}Re.

As a consequence of this measurement of the ground-state mass, overall uncertainty in the mass of the $I^{\pi} = (6^-)$ isomeric state has been correspondingly reduced. This can be included in astrophysical network calculations such as the Brussels Nuclear Library (BRUSLIB) [14].

4. Conclusion

The atomic mass of the isotope ^{190}Re has been measured as $176\,948\,297 \pm 5$ keV corresponding to a mass excess of $-35\,583 \pm 5$ keV. This represents an order of magnitude reduction in the uncertainty compared to previous experiments.

Acknowledgments

ORCID iDs

M R Griffiths ⬤ https://orcid.org/0000-0002-2962-113X
C Wheldon ⬤ https://orcid.org/0000-0001-9137-6051
M Freer ⬤ https://orcid.org/0000-0001-5439-5579
Th Faestermann ⬤ https://orcid.org/0000-0002-6603-8787

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