Determination of ^{181}Re and ^{181}Os atomic masses from the ^{185}Re(α, ^{8}He)^{181}Re reaction

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The atomic mass excesses of ^{181}Re and ^{181}Os were determined to be -46.519 ± 0.016 and -43.49 ± 0.20 MeV from the measured Q value of -26.480 ± 0.014 MeV for the ^{185}Re(α,^{8}He)^{181}Re(g.s.) reaction and the known beta-decay Q value. The results were compared with some predicted values.

I. INTRODUCTION

The ground-state mass is one of the most fundamental quantities of atomic nuclei. Its precise values are useful especially for studying nuclear systematics and decay phenomena. Mass excesses of more than 1600 nuclides have already been measured. Further, many authors[1–14] have been trying to reproduce them from phenomenological, macroscopic, or microscopic calculations. Unknown masses can be predicted by mass formulas or mass relations whose parameters have been extracted from the measured masses. For an accurate prediction, and also for a deeper understanding of the nature of atomic nuclei, the addition and the improvement of experimental mass values are still valuable.

The Q value of α or β decay gives a mass relation between the parent and daughter nuclei. The mass of an unmeasured nucleus can be derived if its decay energy to or from the nucleus of a known mass has been measured. Masses of many neutron-rich nuclei have been determined by Q values of charged-particle emission (α or β decay). On the other hand, proton-rich nuclei do not always decay through the charged-particle emission. Sometimes they decay through the electron capture process whose Q value is usually difficult to be measured. The mass relation of the proton-rich nuclei through β decay is, therefore, often disconnected. For the determination of the mass of proton-rich nuclei, other means also play important roles.

The Q value of two-body reaction gives a mass relation between the residual and target nuclei. The (α, ^{8}He) reaction is very suitable for such mass determination because it can produce many proton-rich nuclei whose masses have not been measured.[15–24] By measuring the Q values of the (α, ^{8}He) reactions on ^{90}Zr, ^{92}Mo, ^{197}Au, and ^{204}Pb, the present authors had determined[25–27] the masses of ^{86}Zr, ^{88}Mo, ^{193}Au, ^{193}Hg, ^{200}Pb, ^{204}Po, ^{208}Rn, ^{212}Ra, and ^{216}Th.

Figure 1 shows a nuclear chart around ^{181}Re. The atomic number (Z) is increasing to the upward, and the neutron number (N) to the right. Nuclides of known mass are shown by bold blocks. Stable nuclides are shown by gray boxes. All the unstable nuclei here decay through β^+ decay. The mass of ^{181}Re can be obtained from the Q-value measurement of the ^{185}Re(α, ^{8}He)^{181}Re reaction. The nuclide ^{181}Os decays to ^{181}Re through an electron capture process whose Q-value measurement is not impossible. The K-to-total ratio of the electron capture has been obtained by x-ray measurement. Since the ratio is strongly dependent on the decay Q value, the latter was derived from the former.[28] The Q value is available for deducing the mass of ^{181}Os from that of ^{181}Re.

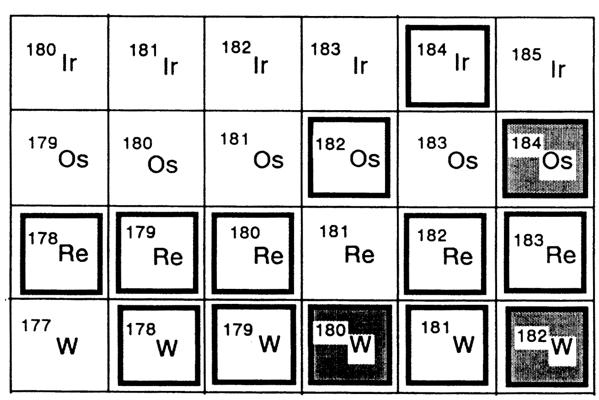

FIG. 1. A nuclear chart around ^{181}Re. The atomic number (Z) is increasing to the upward and the neutron number (N) to the right. Nuclides of the known mass are shown by bold blocks. Stable nuclides are shown by gray boxes.

II. EXPERIMENTAL PROCEDURES AND RESULTS

A. Experimental setup and data taking

A self-supporting foil of enriched (94.8%) ^{185}Os was bombarded by a 65-MeV alpha beam from the Sector-Focusing cyclotron of the Institute for Nuclear Study, University of Tokyo (INS-SF). The thickness of the target foil was 0.64 mg/cm^2. The integrated charges of the beam current was about 0.30 Coulomb. Reaction products were analyzed with the quadrupole-dipole-dipole (QDD) magnetic spectrometer[29] at 8° (with 5 msr). They were detected with a position-sensitive gas proportional counter backed by a large silicon detector.[30]

The counter system consisted of two position counters, an energy-loss counter and an energy counter. The energy counter was a large (11.5 cm long, 2.5 cm high, and 2 mm thick) home-made silicon detector. The counter system was put not along the focal plane of the spectrometer, but perpendicular to the mean trajectory of the particles to cover as wide a momentum range as possible. The position along the focal plane was derived from the information on the two measured positions on the two position counters. The twofold measurement of positions was also useful for suppressing particles of improper incident angles to the counter.

The normal incidence of particles was useful for avoiding the degradation of position resolution by an off-normal incidence of particles to the counter. It is useful also for minimizing the spread of the energy-loss signals by the smallest variation of path length in the counter.

Since the energy-loss signal was generated after the vertical drift of primary charges, the vertical position on the focal plane was deduced from its drift time. The information on the time of flight (TOF) was obtained by the interval between the rf signal from the cyclotron oscillator and the fast signal from the silicon detector.

The energy-loss signal, the energy signal, the vertical-position signal, the TOF signal, and the four signals from both sides of the two position counters were analyzed with analog-to-digital converters. A rough hardware discrimination by the energy-loss signal was made to reduce the unnecessary counts. The eightfold coincident events were recorded on magnetic tapes event by event. The number of the recorded events was about 470 000.

B. Data reduction

Figure 2 shows a scatter plot of the first (abscissa) and the second (ordinate) positions for sampled events. The counts must be distributed on the diagonal line if the characteristics of the two position counters are identical. One can see clearly two lines. The counts on the upper line are of improper incident angle to the counter. The elimination of such counts was very powerful for reduction of the background counts.

Figure 3 shows a scatter plot of the energy (abscissa) and the energy loss (ordinate) for the reaction products after the background suppression by use of the information on the TOF, the energy losses in the two position counters, and the vertical position on the focal plane as

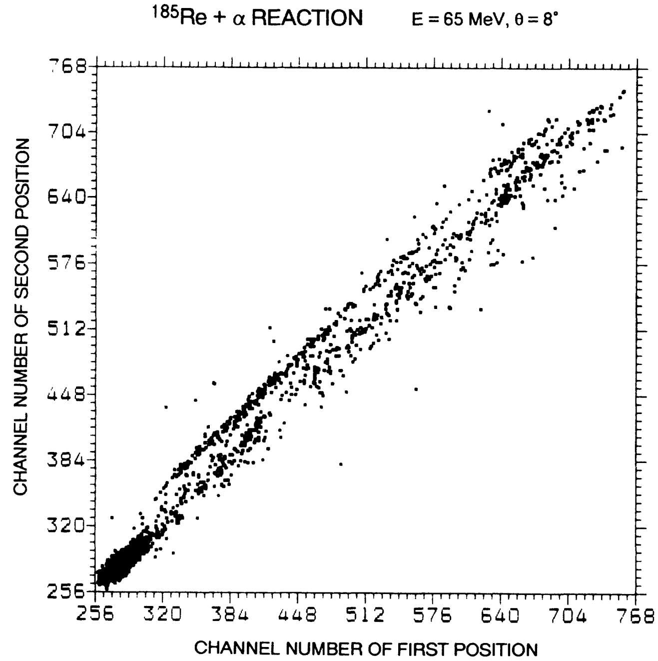

FIG. 2. A scatter plot of the first (abscissa) and the second (ordinate) positions for the particles from the ^{185}Re+α reaction. In order to retain the clearness of the figure, the plotted counts were restricted to those whose energy and energy loss signals were nearly same as those of $^{8}He^{2+}$.

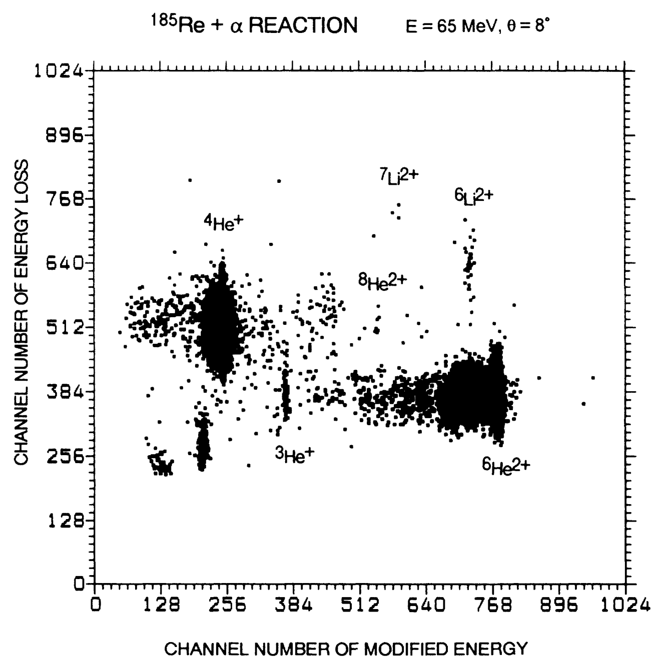

FIG. 3. A scatter plot of modified energy (abscissa) and energy-loss (ordinate) spectra for the particles from the ^{185}Re+α reaction. "Modified" here means that the energy spread within the large energy range was compensated for the better particle identification by means of the position information.

well. The counter system covered as wide an energy range as 5.5% which is much larger than the resolution of the silicon detector. Because the energy is dependent on the position, the energy spread within the wide range was compensated by the position information.

For a fixed magnetic rigidity, energy and energy loss are proportional to Q^2/A and $(AZ/Q)^2$, where Q, A, and Z are the charge, mass number, and atomic number of the particles. The search for the peak of $^8He^{2+}$ from the peak position of $^4He^+$ was easy because the energy losses of these two particles are equal to each other and the energy of the latter is twice as large as the former. We have only to search to the right of the $^4He^+$ peak. The $^8He^{2+}$ peak is well isolated.

Figure 4 shows the central part of the position spectrum of the ^{185}Re(α, ^{8}He) ^{181}Re reaction. Only one peak is seen in the spectrum which covered an excitation energy range of about 1.2 MeV. The low-lying states of ^{181}Re are well known.[31] Only the ground state of ^{181}Re has the spin, parity ($\frac{5}{2}^+$), and Nilson quantum number ($\frac{5}{2}$[402]) same as those of target nucleus ^{185}Re. Since the ^{8}He particles were measured at forward angles, relatively large cross sections can be expected for the transition to the ground state. Further, the spectrum resembles that of the ^{197}Au(α, ^{8}He) ^{193}Au reaction,[25] where the ground state of ^{193}Au was more than five times as strongly excited as the low-lying states under the same experimental conditions. Thus we can assign the peak to the ground state of ^{181}Re. From the measured count of 5, the differential cross section of the ground-state transition was obtained to be 0.54±0.24 nb/sr.

While $^8He^{2+}$ particles were detected, $^6He^{2+}$ particles which correspond to low-lying states in ^{183}Re also impinged on the counter. Figure 5 shows the momentum spectrum of the $^6He^{2+}$ particles. Eight peaks whose excitation energies are indicated in the figure correspond to the known low-lying states. Since these excitation energies are known with precision better than 1 keV,[31] they are available for the calibration of the (α, ^{8}He) spectrum. The uncertainties of the Q values of the ^{185}Re(α, ^{6}He) ^{183}Re reaction is 9 keV.

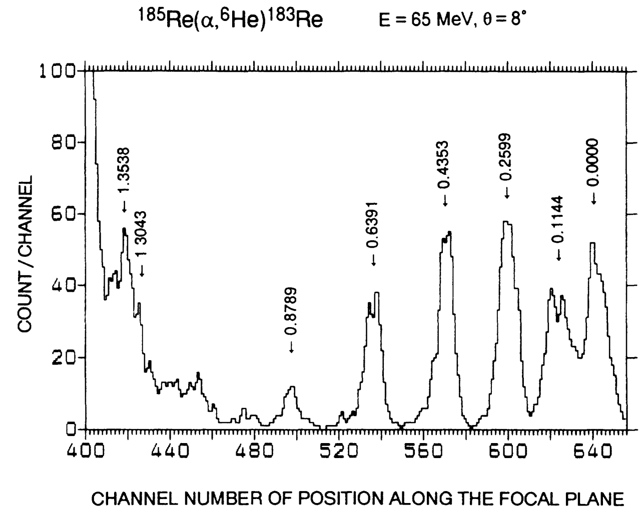

FIG. 5. A position (momentum) spectrum of the ^{185}Re(α, ^{6}He) ^{183}Re reaction. Identified peaks were indicated by the excitation energies in MeV.

From kinematical calculations which took into account the energy loss in the target we obtained a relation between the channel number and the orbit radius in the magnetic spectrometer. The calibration points were fitted by a smooth curve. From the calibration and the peak position of the (α, ^{8}He) spectrum, the Q value of the ^{185}Re(α, ^{8}He) ^{181}Re reaction was determined to be −26.480 MeV.

The centroid of the (α, ^{8}He) peak was determined with precision of 1.9 channels. This value corresponds to 9 keV uncertainty of the reaction Q value. The standard deviation of the calibration points from the fitted curve is 0.007 cm (0.8 channels). Its effect on the Q value is 3 keV. The uncertainty of the incident energy was estimated to be 19 keV from a 4-mm slit aperture of the beam-analyzing system. Its effects on the reaction Q value was 5 keV. This unexpectedly small value is due to the simultaneous measurement of (α, ^{8}He) and (α, ^{6}He) spectra. Because the uncertainty of the target thickness causes a

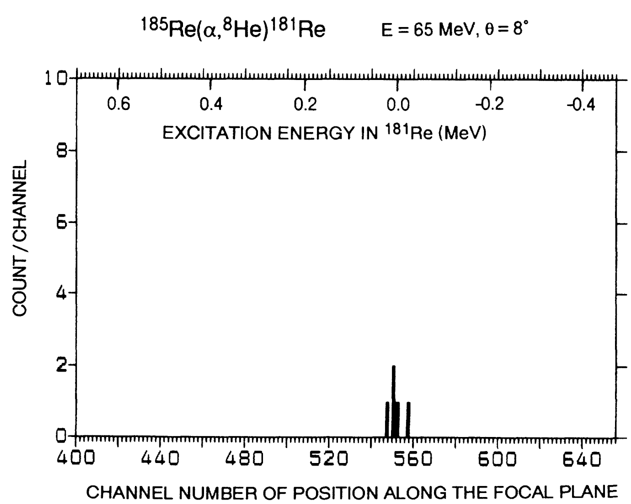

FIG. 4. A position (momentum) spectrum of the ^{185}Re(α, ^{8}He) ^{181}Re reaction. Only the region of interest is shown. The excitation energy range of about 1.2 MeV is covered in the figure.

TABLE I. Origins and their quantities contributing to the uncertainty of the Q value of the ^{185}Re(α, ^{8}He) ^{181}Re reaction.

Uncertainty of	Effect on the Q value (keV)
Q value of calibration	9
Peak position	9
Calibration points	3
Incident energy	5
Target thickness	1
Total	14

large uncertainty of the reaction Q value, the thickness was measured carefully with an α gauge. The decrease of range of α particles emitted from an ^{241}Am source in the air by an insertion of the target gave the thickness. The uncertainty of the target thickness was 5% (0.03 mg/cm^2). The effect on the reaction Q value was 1 keV.

The origins of the uncertainty of the reaction Q value were listed in Table I with their quantities. The total uncertainty amounted to 14 keV.

III. DISCUSSION

From the measured Q value of -26.480 ± 0.014 MeV and the known mass excesses[13] of -43.826 ± 0.003, 2.425 ± 0.000, and 31.598 ± 0.007 MeV for ^{185}Re, ^{4}He, and ^{8}He, we obtained -46.519 ± 0.016 MeV as the mass excess of ^{181}Re for the first time.

The known Q values of the β^+ decay is 3.03 ± 0.20 MeV (from ^{181}Os to ^{181}Re).[28,32] One can derive the value of -43.49 ± 0.20 MeV for the mass excess of the parent nuclide ^{181}Os. Most of the large uncertainty of the mass is due to that of β^+-decay Q value.

Table II compares the obtained mass excesses with some predicted ones.[1–14] Most of the predicted values are scattered around the measured ones. Large deviation (more than 1.0 MeV) are seen for the calculations by Tachibana *et al.*[10] for both ^{181}Re and ^{181}Os. Smaller deviations are seen for ^{181}Os by Comay *et al.*,[8] Spanier and Johannson,[11] and Masson and Jänecke.[13] Other values agree with the experiment within the indicated theoretical uncertainties, although they are not shown for all the predictions.

Calculations by Wapstra *et al.*[2,4,14] used masses of neighboring nuclides. Because the masses of neighboring nuclides of ^{181}Re were known, they were able to interpolate the known masses. They predicted twice as good values as the indicated uncertainties. On the other hand, since they were unable to interpolate any known masses for the prediction of ^{181}Os mass, they had to refer to the same β^+-decay Q value as the present report. Because the uncertainty of the Q value is very large, further comparison is here meaningless. Future improvement of the Q-value measurement will make the comparison meaningful.

Although the measured cross section was very small (0.54±0.24 nb/sr), we were able to obtain a background-free spectrum (Fig. 3). The present counter system proved to be useful for detecting very rare events whose cross sections are as small as 0.1 nb/sr, which corresponds to one count in the spectrum.

IV. SUMMARY

The atomic mass excess of ^{181}Re was determined to be -46.519 ± 0.016 MeV from the measured Q value of -26.480 ± 0.014 MeV for the ^{185}Re(α, ^{8}He) ^{181}Re (g.s.)

TABLE II. The measured and the predicted mass excess of ^{181}Re and ^{181}Os.

Authors	Mass excess (MeV) ^{181}Re	^{181}Os
Experiment		
Present	-46.519 ± 0.016	-43.49 ± 0.20
Predictions		
Garvey *et al.*[a]	-46.17	-43.17
Uno-Yamada (c)[b]	-46.379 ± 0.406	-43.789 ± 0.746
Uno-Yamada (l)[c]	-46.417 ± 0.455	-43.930 ± 0.616
Dussel *et al.*[d]	-46.77	-43.81
Möller-Nix[e]	-46.98	-43.90
Möller *et al.*[f]	-46.67	-43.72
Comay *et al.*[g]	-46.59 ± 0.52	-44.09 ± 0.68
Satpathy-Nayak[h]	-46.66	-43.73
Tachibana *et al.*[i]	-44.60	-42.13
Spanier-Johannson[j]	-46.81	-44.30
Jänecke-Masson[k]	-46.30	-43.84
Masson-Jänecke[l]	-46.39	-44.14
Wapstra *et al.* (1977)[m]	-46.440 ± 1.000	-43.410 ± 1.000
Wapstra *et al.* (1983)[n]	-46.560 ± 0.100	-43.530 ± 0.220
Wapstra *et al.* (1986)[o]	-46.460 ± 0.100	-43.530 ± 0.250

[a]Reference 1.
[b]Reference 3 (constant).
[c]Reference 3 (linear).
[d]Reference 5.
[e]Reference 6.
[f]Reference 7.
[g]Reference 8.
[h]Reference 9.
[i]Reference 10.
[j]Reference 11.
[k]Reference 12.
[l]Reference 13.
[m]Reference 2.
[n]Reference 4.
[o]Reference 14.

reaction for the first time. We obtained the mass excess of -43.49 ± 0.20 MeV for ^{181}Os as well by use of the known Q value of the β decay.

The predictions by Wapstra *et al.* had given good values for ^{181}Re. The precision was found to be twice as good as the indicated values.

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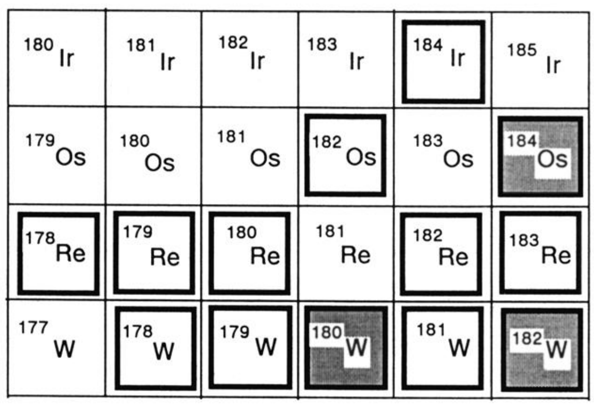

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