Determination of ^{86}Zr and ^{88}Mo atomic masses by the (α, ^{8}He) reactions on ^{90}Zr and ^{92}Mo

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The atomic mass excesses of ^{86}Zr and ^{88}Mo were determined to be -77.807 ± 0.031 and -72.703 ± 0.021 MeV from the measured Q values of -40.136 ± 0.030 and -43.278 ± 0.020 MeV for the ^{90}Zr(α,^{8}He)^{86}Zr(g.s.) and ^{92}Mo(α,^{8}He)^{88}Mo(g.s.) reactions. The results were compared with some predicted values.

The ground-state mass is one of the most fundamental quantities of atomic nuclei. If the mass has not been measured, it can be predicted by mass formulas or mass relations whose parameters have been extracted from the measured ones. For an accurate prediction, and for a deeper understanding of the nature of atomic nuclei, the addition of experimental mass values is useful.

The Q value of two-body nucleon transfer reaction connects the mass of the residual nucleus with that of the target nucleus. The (α,^{8}He) reaction is very suitable for such mass determination because it can produce many nuclei whose masses are unknown. By measuring the Q value of the ^{197}Au(α,^{8}He)^{193}Au reaction, we had determined[1] the masses of ^{193}Au and ^{193}Hg.

Here we report results of the first determination of the masses of ^{86}Zr and ^{88}Mo from the Q-value measurements of the ^{90}Zr(α,^{8}He)^{86}Zr and ^{92}Mo(α,^{8}He)^{88}Mo reactions. The predicted values by Wapstra *et al.*,[2,3] which utilized masses of neighboring nuclei, have not been improved since 1983.

Self-supporting foils of enriched (about 95%) ^{90}Zr and ^{92}Mo were bombarded by a 65-MeV alpha beam from the Sector-Focusing cyclotron of the Institute for Nuclear Study (INS-SF). The thicknesses of the target foils were 0.3 and 1.0 mg/cm^2 for ^{90}Zr and ^{92}Mo, respectively. The integrated charges of the beam were 73 and 21 mC. Reaction products were analyzed with the quadrupole-dipole-dipole (QDD) magnetic spectrometer[4] at 8° (with 5 msr). They were detected with a position-sensitive gas proportional counter backed by a large silicon detector.[5]

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 position counters were long enough to cover the energy counter. 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 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.

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 of 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 and recorded on magnetic tapes event by event. The numbers of the recorded counts were about 1 220 000 and 530 000 for the ^{90}Zr$+\alpha$ and ^{92}Mo$+\alpha$ reactions.

A large number of inelastically scattered ^{4}He particles hit the counter and caused many background counts because of the larger magnetic rigidity of the incident alpha beam than ^{8}He^{2+} particles. The identification of ^{8}He^{2+} particles was much more difficult than the ^{197}Au(α,^{8}He)^{193}Au case[1] where the magnetic rigidity of ^{8}He^{2+} particles was larger than ^{4}He^{2+} particles.

Figures 1 and 2 show contour plots of the energy (abscissa) and the energy loss (ordinate) for the reaction products after the background suppression by the signals

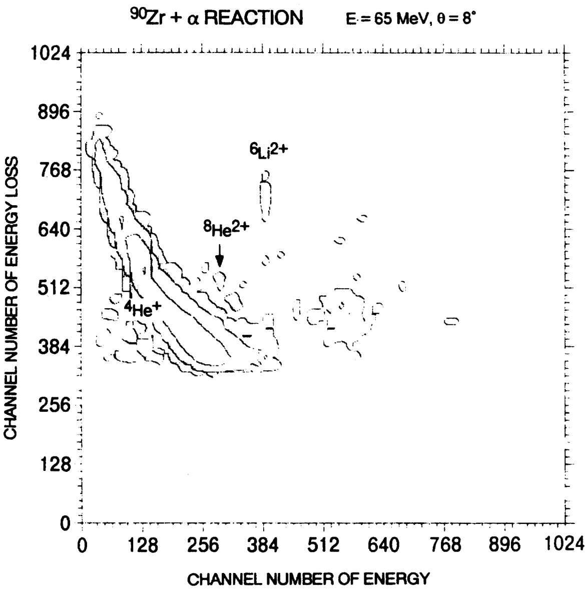

FIG. 1. A contour plot of energy (abscissa) and energy-loss (ordinate) spectra for the $^{90}Zr+\alpha$ reaction. Although the full channel numbers are shown to be 1024×1024 channels, they have been reduced to 64×64 blocked channels. The contour levels are in logarithmic steps. The solid contours indicate 1, 10, 100, and 1000 counts per block (16×16 channels). The dotted contours indicate 2 or 5 times that.

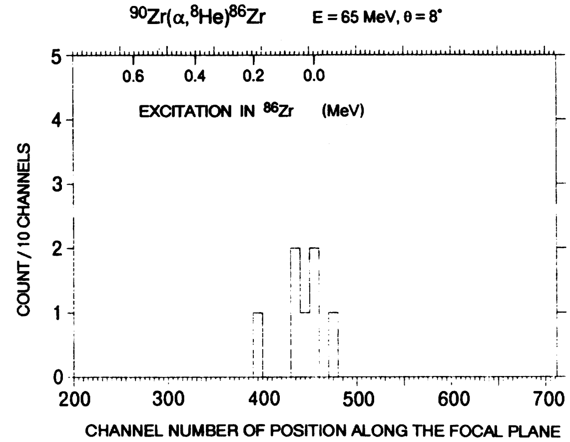

FIG. 3. A position (momentum) spectrum of the $^{90}Zr(\alpha,{}^{8}He)^{86}Zr$ reaction. The count near 400 channels might be from other isotopes of Zr in the target.

of the TOF, the incident angle to the counter, the energy losses in the two position counters, and the vertical position on the focal plane. A detailed data reduction procedure is reported in Ref. 5. For a fixed magnetic rigidity, the energy and the 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 particle. Each nuclide must be located not on a locus, but at a spot in the spectra. The notable loci (hyperbolae) were caused by the energy change of particles after the magnetic analysis. In the $^{90}Zr+\alpha$ reaction, the incident angle information was very useful to eliminate particles which were scattered from the wall of the vacuum chamber. Unfortunately, a group of such particles impinged on the counter at the normal angle in the $^{92}Mo+\alpha$ case. The information of the incident angle was unavailable in the latter case.

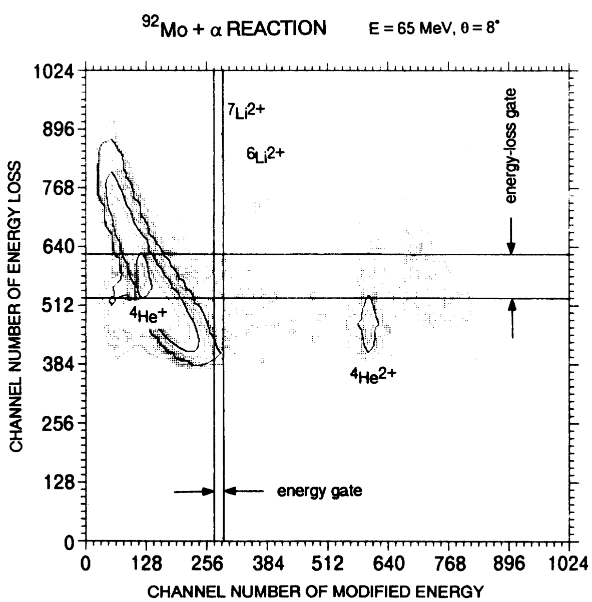

FIG. 2. Same as Fig. 1 but for the $^{92}Mo+\alpha$ reaction. Contours higher than 2 are shown. Since the peak of $^{8}He^{2+}$ is not clearly isolated, the gates of the energy and the energy loss are shown.

The search for the peak of $^{8}He^{2+}$ from the peak position of $^{4}He^{+}$ 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. The $^{8}He^{2+}$ peak was well isolated in the $^{90}Zr+\alpha$ reaction. Since the information on the incident angle was not used in the $^{92}Mo+\alpha$ case, the peak of $^{8}He^{2+}$ was not clearly isolated.

Figures 3 and 4 show the position spectra of the $^{90}Zr(\alpha,{}^{8}He)^{86}Zr$ and $^{92}Mo(\alpha,{}^{8}He)^{88}Mo$ reactions. Only

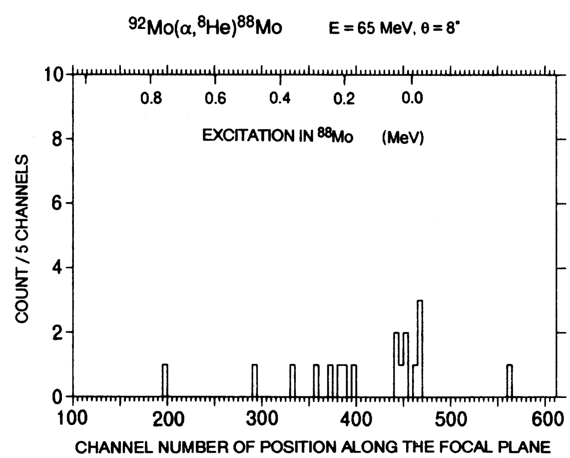

FIG. 4. A position spectrum of the $^{92}Mo(\alpha,{}^{8}He)^{88}Mo$ reaction.

the ground states should appear in the indicated energy range because the residual nuclei are even-even. The corresponding peaks were easily identified. The differential cross sections of the ground-state transitions of the $^{90}Zr(\alpha,{}^{8}He)^{86}Zr$ and $^{92}Mo(\alpha,{}^{8}He)^{88}Mo$ reactions were 2.8 ± 1.1 and 4.6 ± 1.5 nb/sr.

We calibrated the spectra by detecting alpha particles from $^{12}C(\alpha,\alpha)^{12}C$ scattering at backward angles at the same magnetic field strength as the $(\alpha,{}^{8}He)$ measurements. The angle where the magnetic rigidity of the alpha particles coincide with that of $^{8}He^{2+}$ was determined. From kinematical calculations which took into account the energy losses in the targets, the reaction Q values were determined to be -40.136 and -43.278 MeV for the $^{90}Zr(\alpha,{}^{8}He)^{86}Zr$ and $^{92}Mo(\alpha,{}^{8}He)^{88}Mo$ reactions. The energy scales of the excitation of the residual nuclei are shown in Figs. 3 and 4.

The centroids of the peaks were determined with precisions of ±8.1 and ±3.9 channels for the $^{90}Zr(\alpha,{}^{8}He)^{86}Zr$ and $^{92}Mo(\alpha,{}^{8}He)^{88}Mo$ reactions. These values correspond to ±26 and ±11 keV uncertainties of the reaction Q values. The uncertainty of the incident energy was estimated to be ±23 keV from a 5-mm slit aperture of the beam-analyzing system. Its effects on the reaction Q values were ±14 and ±15 keV. The target thicknesses of ^{90}Zr and ^{92}Mo were (0.30 ± 0.03) and (1.02 ± 0.02) mg/cm^2. The effects on the reaction Q values were ±5 and ±4 keV. The uncertainties of the known mass excesses[3] of the nuclei ^{90}Zr, ^{92}Mo, and ^{4}He were ±2, ±4, and less than ±1 keV. The total uncertainties amounted to ±30 and ±20 keV for the $^{90}Zr(\alpha,{}^{8}He)^{86}Zr$ and $^{92}Mo(\alpha,{}^{8}He)^{88}Mo$ reactions.

From the measured Q value of -40.136 ± 0.030 MeV for the $^{92}Zr(\alpha,{}^{8}He)^{86}Zr$ reaction and the known mass excesses[3] of -88.770 ± 0.002, 2.425 ± 0.000, and 31.598 ± 0.007 MeV for ^{90}Zr, ^{4}He, and ^{8}He, we obtained -77.807 ± 0.031 MeV as the mass excess of ^{86}Zr. Similarly, from the measured Q value of -43.278 ± 0.020 MeV for the $^{92}Mo(\alpha,{}^{8}He)^{88}Mo$ reaction and the known mass excess of -86.809 ± 0.004 MeV for ^{92}Mo, we obtained -72.703 ± 0.021 MeV as the mass excess of ^{88}Mo.

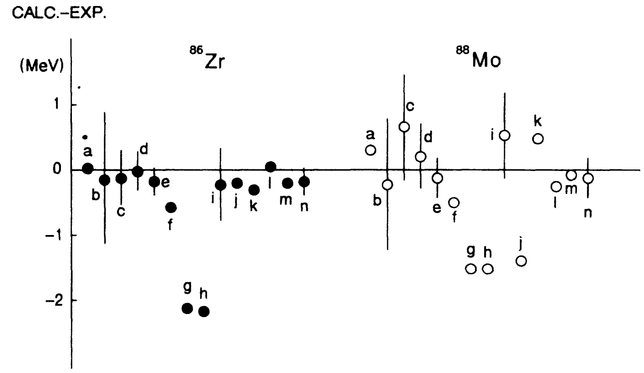

FIG. 5. A comparison of predicted mass excesses with the measured ones for ^{86}Zr and ^{88}Mo. Closed circles show predicted values of ^{86}Zr, and open circles for ^{88}Mo. The tags from "a" to "n" indicate following references: (a) Ref. 6, (b) Ref. 7, (c,d) Ref. 8, (e) Ref. 2, (f) Ref. 9, (g) Ref. 10, (h) Ref. 11, (i) Ref. 12, (j) Ref. 13, (k) Ref. 14, (l) Ref. 15, (m) Ref. 16, and (n) Ref. 3.

Figure 5 compares them with some predicted masses.[2–3,6–16] Most of the predicted values are scattered around the measured ones. Large deviations are seen for calculations by Möller and Nix (g),[10] Möller, Myers, Swiatecki, and Treiner (h),[11] and Satpathy and Nayak (j).[13] Other values agree with the experiment within the indicated theoretical uncertainties, although they are not shown for all the predictions. In the predictions by Uno and Yamada,[8] the "linear" shell calculation (d) had predicted better than the "constant" shell one (c) because of the larger number of parameters.

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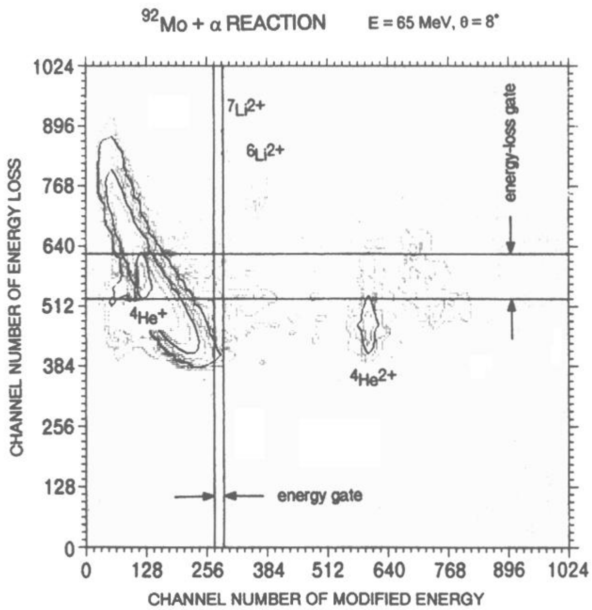

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