Masses of ^{98}Pd, ^{99}Pd, and ^{100}Pd

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The Q values of the reactions ^{96}Ru(^{16}O,$^{14-12}$C)$^{98-100}$Pd have been simultaneously measured using a quadrupole-dipole-dipole-dipole magnetic spectrometer. The result for the (^{16}O,^{14}C) reaction is $Q=-12.529\pm0.020$ MeV, from which we deduce the first measured mass excess of ^{98}Pd: -81.303 ± 0.022 MeV. The Q value for the (^{16}O,^{13}C) reaction is determined to be -11.723 ± 0.020 MeV, from which we obtain -82.214 ± 0.022 MeV for the mass excess of ^{99}Pd. This value is the first direct measurement of the mass of ^{99}Pd, and disagrees with a previously tabulated value. For the (^{16}O,^{12}C) reaction, $Q=-5.599\pm0.026$ MeV, which leads to a mass excess for ^{100}Pd of -85.213 ± 0.027 MeV, in agreement with a previous measurement using light ions. A mass excess of -87.138 ± 0.022 MeV for ^{106}Cd, measured with the ^{104}Pd(^{16}O,^{14}C) reaction, is also in excellent agreement with a tabulated value.

[NUCLEAR REACTIONS ^{16}O + ^{96}Ru, $E=70$ MeV; measured $E_{^{14}C}$, $E_{^{13}C}$, $E_{^{12}C}$; ^{98}Pd, ^{99}Pd, ^{100}Pd deduced level, Q, masses; QDDD magnetic spectrometer.]

INTRODUCTION

The large variety of possible heavy-ion induced transfer reactions allows many nuclides to be reached whose masses are poorly known or have not been measured. For example, a survey of the 1977 Mass Table of Wapstra and Bos[1] reveals that there are 43 nuclides, whose masses are either not known or uncertain by at least 100 keV/c^2, which may be measured with the (^{16}O,^{14}C) reaction alone. The cross sections for these reactions might be expected to be large (10 to 100 μb/sr) since the Q values are nearly optimum. One goal of the present study is to develop methods for routinely determining Q values for heavy-ion induced reactions, in spite of large potential errors due to severe kinematic and target thickness effects.

The decision to measure the unknown mass excess of ^{98}Pd was made with the additional goal of confirming a preliminary assignment[2] of γ-ray transitions to ^{98}Pd by directly observing the yrast $J=0^+$, 2^+, and 4^+ states of ^{98}Pd in the ^{14}C spectrum. The mass excesses of ^{99}Pd and ^{100}Pd have been measured as well, since the spectra for the (^{16}O,^{13}C) and (^{16}O,^{12}C) reactions are obtained at the same spectrometer magnetic field. This is the first direct measurement for ^{99}Pd and disagrees with a previously tabulated value,[1] as will be shown below. For ^{100}Pd, the measurement is in agreement with a value measured previously[3] using the ^{102}Pd(p,t)^{100}Pd reaction.

While the experimental method used here is not essentially new, the use of elastic scattering to calibrate Q-value measurements has not been exploited previously. Therefore, to check the entire method, the accurately known mass excess of ^{106}Cd has been remeasured using the reaction ^{104}Pd(^{16}O,^{14}C)^{106}Cd. The resulting value[1] agrees with the established value.

Although a magnetic spectrometer can in principle be used to make absolute Q-value measurements from a knowledge of the magnetic field and radius of curvature, the more conventional procedure is to interpolate the unknown Q value from accurately known Q values by observing both the unknown and the calibration reactions in the spectrometer under conditions as nearly identical as possible.

In an ideal case, several reactions with known Q values, which bracket the reaction of unknown Q value would be observed for fixed scattering angle, beam, and target. This is not always possible, and

one or more of the conditions of the reaction must be altered. Corrections for these changes can be large and may introduce large systematic errors in the Q value. In the method used here, the reliability of the measurement is enhanced by keeping the target, projectile, beam energy, and scattering angle the same, and changing only the ejectile to be used for the calibration. Elastic scattering is chosen as the calibration because it is observable with large yield and yet the kinematics are similar enough to few-nucleon transfer to greatly attenuate the effect of any errors in the absolute beam energy or scattering angle on the measured Q value. The magnetic rigidity of the elastically scattered ions can also generally be chosen to be similar to that for the reaction, since several charge states of the elastic ions are available with sufficient yield. Finally, an attempt has been made to directly measure the systematic errors due to the remaining small differences in the elastic calibration and the reactions. Measurements have been made to correct for the effects of kinematics, field dependence and hysteresis of the magnet, target thickness, and nonideal position determination in the focal plane detector.

EXPERIMENT

The reactions ^{96}Ru(^{16}O,$^{12-14}$C)^{100,99,98}Pd and ^{104}Pd(^{16}O,^{14}C)^{106}Cd were observed in the quadrupole-dipole-dipole-dipole (QDDD) spectrometer at 40° and 45°, respectively, following bombardment by a 70 MeV ^{16}O beam from the BNL MP Tandem Van de Graaff. The ^{96}Ru targets were isotopically enriched to 98% and the ^{104}Pd targets were enriched at 90%. The beam spot position on the target was monitored by using two Si surface barrier detectors located at 15° on either side of the beam to record elastic scattering. Carbon ions were detected and identified in the focal plane by a dual volume, position sensitive proportional counter filled with pure isobutane gas at a pressure of 240 Torr. The entrance window of this counter was equivalent to 26 μm of Mylar, and the front and rear volumes were separated by 3 μm of aluminized Mylar. Identification of the carbon ions was made by observing the energy loss signals in the front (1.5 cm thick) and rear (8 cm thick) gas proportional counters (ΔE and E, respectively). Figure 1 displays the ΔE vs E particle identification spectrum for the ^{96}Ru + ^{16}O experiment: The separation of each of the three carbon ions from all other ions incident on the detector is unambiguous.

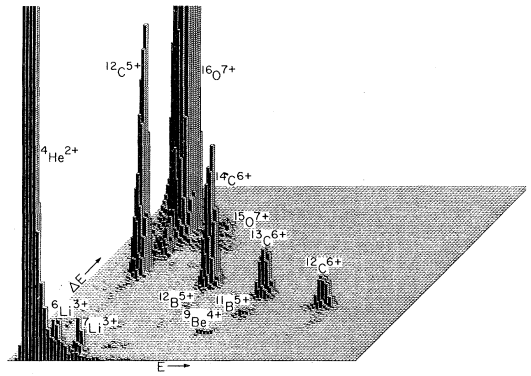

FIG. 1. A particle identification spectrum for reactions induced by 70 MeV ^{16}O on ^{96}Ru. Gates around the ^{12}C, ^{13}C, and ^{14}C peaks were used to select events for the spectra shown in Fig. 5.

Position determination was made by using charge division on a resistive metal wire in the front proportional counter. To monitor the experiment, the charge division was performed by an analog divider circuit; but for the final data analysis the division, with corrections to be discussed below, was performed numerically from event-mode tapes using pulse height data for the left and right ends of the wire. The ultimate position resolution of the detector, limited by electronic noise, was 1.5 mm (equivalent to about 10 keV). Pulse height data for the rear proportional counter were also recorded on tape so that gates could be set on ΔE and E in the off-line analysis to exclude all but the appropriate carbon ion.

Elastic scattering of ^{16}O ions with the same beam energy, target, and scattering angle were used to calibrate each reaction. The magnetic field in the spectrometer dipoles and the field in the spectrometer quadrupole element used to correct for kinematics were changed to focus $^{16}O^{7+}$ ions on the detector. This charge state was chosen to match best the rigidity of the 6 + carbon ions. In addition, the opening of the spectrometer slits in the reaction plane was reduced from 50 to 10 mrad to better define the central scattering angle for the strongly angle dependent elastic scattering cross section.

In order to minimize errors in reproducing and defining the magnetic field throughout the spectrometer, the magnet current was cycled at the beginning of the experiment, and the magnetic field was changed slowly and only in an increasing direction between successive measurements. The

magnet current was cycled whenever a decrease in magnetic field was required. The elastic calibration was repeated several times during the experiment to estimate any residual field histories.

Energy losses in the targets were measured, with the QDDD at 0°, by attenuating the ^{16}O beam to a few hundred particles per second, and observing the beam peak position in the focal plane detector both with and without the target. The resulting energy losses calculated with the elastic calibration are listed in Table I. Measurements made at the beginning and end of the experiment indicated that the target thickness increased by about 10% during the experiment. Energy losses in the target were measured for both $^{16}O^{6+}$ and $^{16}O^{7+}$ ions. The energy loss is slightly higher for the 7+ ion. Other Ru and Pd targets also exhibit this effect. Energy losses for the carbon ions were estimated from the measured ^{16}O values using the tabulated stopping powers of Northcliffe and Schilling.[4]

CALIBRATION PROCEDURE

The use of elastic scattering as a calibration alters several important experimental conditions from those for the reactions being studied. In particular, the magnetic fields in the spectrometer and the energy losses of the ions in the target and detector differ for the two. The corrections for effects resulting from these differences that must be made to obtain accurate Q values are discussed in this section.

Because of the small field dependence of the location of the effective field boundaries in the QDDD, the magnetic rigidity of a particle arriving at a particular point in the focal plane is not exactly proportional to the magnetic field measured by a nuclear magnetic resonance (NMR) probe. This field dependence of the measured rigidity has been determined by observing elastic scattering of ^{16}O and ^{32}S beams from thin gold targets for a range of charged states and incident energies which span the range of magnetic fields from 4 to 15 kG (the present fields required are ~7 kG). These data can be parametrized as

$$B_c = B_m(\alpha + \beta B_m) ,$$

where B_c is the field that yields the correct rigidity and B_m is the field measured by an NMR probe. The field dependent slope β is determined by fitting the data for B_c/B_m vs B_m for a series of charge states of the same incident beam, so that ratios of B_c are known. The value found is $\beta = (8.9 \pm 1.5) \times 10^{-4}$ kG^{-1}. The absolute calibration of the QDDD, given by α, is unimportant for these measurements, since two similar ion rigidities are being compared and the field dependence is small. The stated error in the field dependence leads to an error in deduced Q values of 6 keV for the conditions of this experiment.

The quadrupole field of the multipole element, which is used to compensate for the reaction kinematics, changes the dispersion of the QDDD. Since the kinematics of the reaction are not identical to those for the elastic scattering calibration, a correction for the different dispersion must be made. This is done by correcting an observed peak channel number x for the strength of the quadrupole field M_Q,

$$x_c = \frac{x - x_0}{1 - \gamma M_Q} + x_0 ,$$

where x_0 is the channel number corresponding to the central ray. The value for the constant $\gamma = 0.29 \pm 0.02$ was determined by observing elastic scattering of protons for various values of M_Q. The uncertainty in γ and in determining x_0 lead to an uncertainty of 10 keV for the deduced Q values.

The complete calibration scheme for the spectrometer and focal plane detector, incorporating the corrections discussed above, is diagrammed in Fig. 2. The calibration polynomial is obtained by observing the channel number for the elastic scattering peak centroid for a series of different field settings which span the detector. This set of channel numbers, corrected for the dispersion change, and the radii of curvature corrected for the field-dependent calibration, ρ_c, are then used to obtain a cubic polynomial by least squares fitting. This polynomial, plus the field and dispersion corrections can then be used to determine the magnetic rigidity, and (via the kinematics) the Q value

TABLE I. Target energy losses measured in beam with the QDDD magnetic spectrometer located at 0° by using a 70 MeV ^{16}O beam. Both targets were evaporated onto 20 μg/cm^2 carbon backings. The energy losses were measured before and after the experiment and for both 6^+ and 7^+ charge states of the beam.

Target	ΔE(MeV) before	(6^+) after	ΔE(MeV) 6^+	(After) 7^+
^{96}Ru	0.245	0.273	0.273	0.308
^{104}Pd		0.373	0.373	0.385

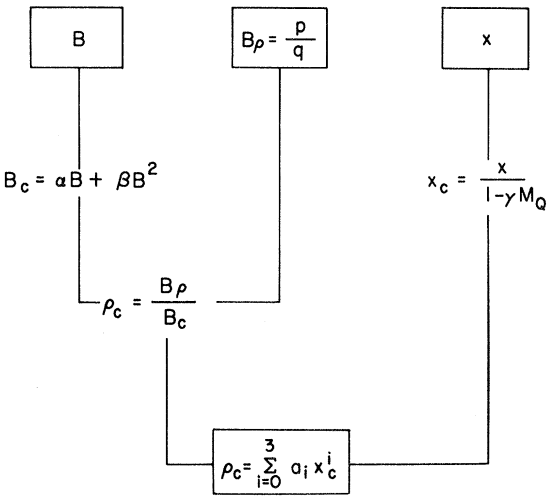

FIG. 2. The calibration procedure for the QDDD and focal plane detector. The channel number x, magnetic field B, and ion momentum p, are related by the calibration such that, given any two, the third can be determined. The coefficients a_i are the result of the calibration. The constants α, β, and γ are determined by seperate experiments, as described in the text.

corresponding to a specified channel number and magnetic field.[5]

The calculation of a position spectrum from the pulse-height signals produced at the two ends of the resistive charge division wire by a charged particle also requires corrections to produce peak centroids which are independent of the energy loss and range in the detector. The presence of electronic offsets in the signals from the left and right end of the wire (S_L and S_R, respectively), would cause the position computed as $x = S_L/(S_L + S_R)$ to depend on the total pulse height (energy loss). This would then cause a shift in computed position between the elastic calibration and the reactions, and hence is a potential source of systematic error in the deduced Q values. This error can be large because the energy losses of the oxygen and carbon ions differ by as much as a factor of 2.5 in the front (position sensitive) volume of the detector. To remove the effects of any electronic offsets, an extensive elastic calibration was recorded with three different bias voltages on the position sensing proportional wire. This provides three calibrations which should be identical in the absence of electronic offsets. The observed pulse heights S_i from each end of the wire were transformed into a "true" pulse height by

$$T_i = C_{0,i} + C_{1,i}S_i + C_{2,i}S_i^2, \quad i = \text{left or right.}$$

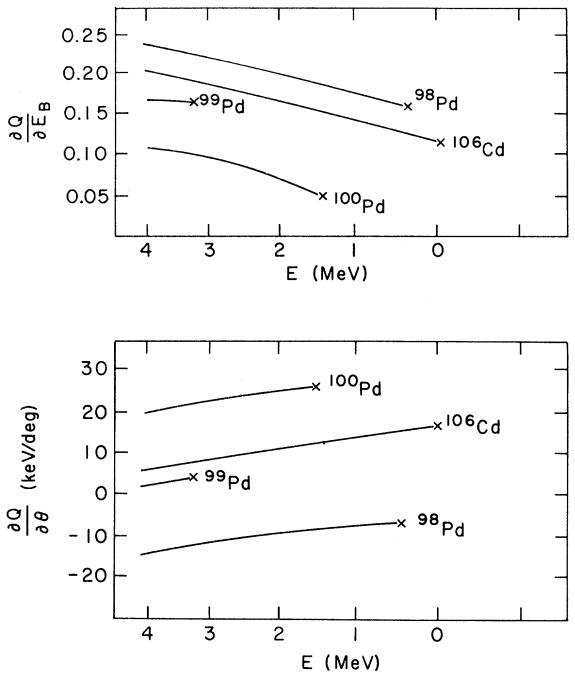

FIG. 3. The calculated change in the deduced Q value for the ^{96}Ru(^{16}O,$^{12-14}$C) reactions and the ^{104}Pd(^{16}O,^{14}C) reaction with changes in the beam energy or the scattering angle when an elastic scattering peak is observed at the same position on the focal plane as a calibration. The abscissa is the excitation energy of ^{106}Cd. All ground states are marked by an $\times$.

The position computed with these true pulse heights should not depend on the bias voltage. A least squares procedure was used to adjust the six parameters $C_{0,L}$, $C_{1,L}$, . . . ,$C_{2,R}$ to minimize the variation in computed position for the three bias voltages. The root-mean-square variation in the computed positions (using the best fit parameters) has been assigned as an error due to uncorrected

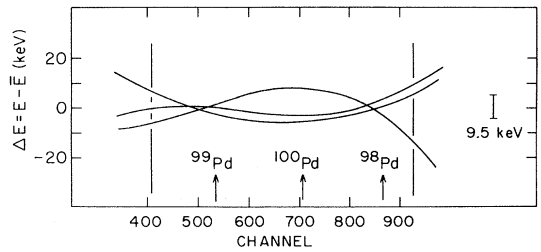

FIG. 4. The deviation from the average of three independent calibrations made with ^{16}O+^{96}Ru elastic scattering as a function of the focal plane position. The locations of the ground states of $^{98-100}$Pd from the ^{96}Ru(^{16}O,$^{12-14}$C) reaction are indicated.

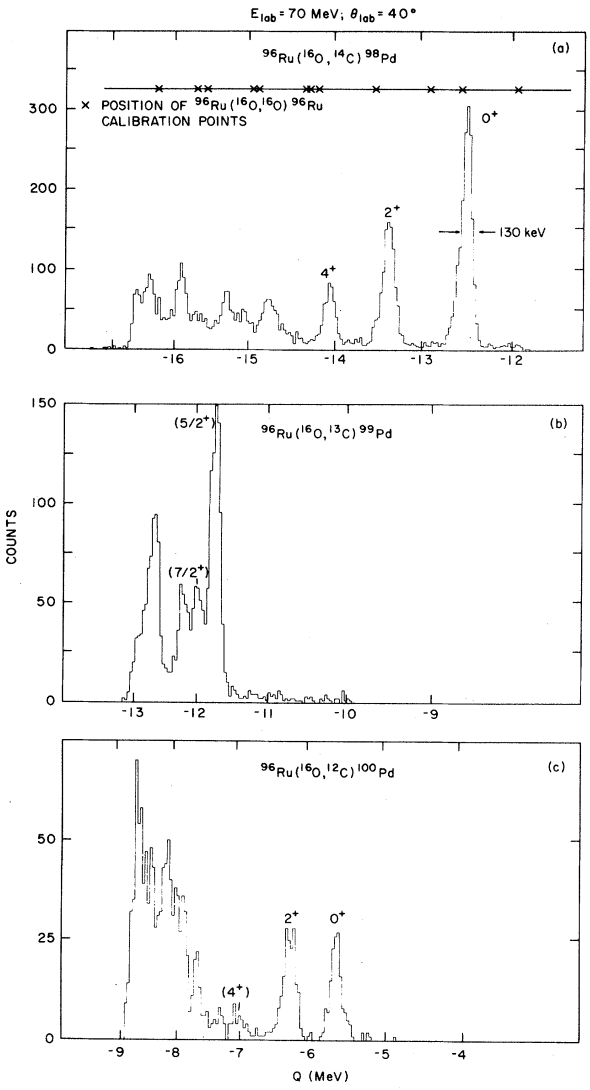

FIG. 5. Computed Q-value spectra for the ^{96}Ru(^{16}O,$^{12-14}$C) reactions. The position in the focal plane detector has been corrected and converted to Q values by the calibration procedure described in the text. Positions of the elastic scattering calibration are shown in the top panel.

amplitude dependence in the position determination in Table III.

Figure 3 shows the kinematic dependence on energy and scattering angle of the deduced Q values for the reactions studied here when elastic scattering is used for a calibration. Since the derivatives $\partial Q/\partial E_B$ and $\partial Q/\partial\theta$ are small relatively independent of excitation energy, even large uncertainties in beam energy ($\Delta E_B = 75$ keV) and scattering angle ($\Delta\theta = 0.5°$) result in small errors in the deduced

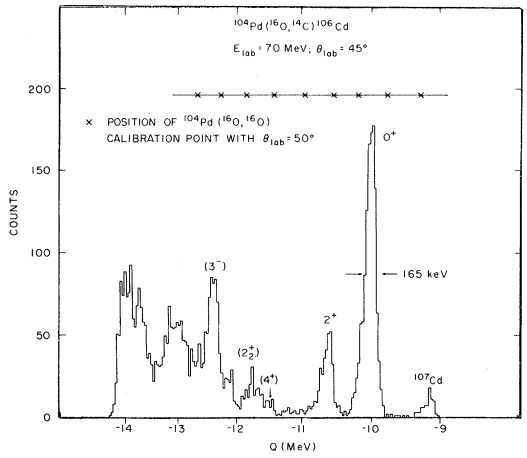

FIG. 6. Deduced Q-value spectrum for the ^{104}Pd(^{16}O,^{14}C)^{106}Cd reaction.

Q values ($\Delta Q = 15$ keV).

Two additional corrections to the positions for the different ions have been considered and found to be small. Since the ions enter the proportional counter at an average angle of about 45°, both multiple scattering in the window and the increased stopping power as the ions slow down in the position sensing volume will shift peak centroids toward larger rigidities. These effects have been computed to cause less than a 1 keV shift in the relative peak positions for oxygen and carbon ions.

As a measure of all other uncertainties in the calibration procedure, the calibrations made at three different times during the experiment have been compared. Figure 4 shows the deviation of each of the three calibrations from the average of all three. This average calibration was used to compute the Q values. Over most of the focal plane the maximum deviation is less than 10 keV. These differences are presumed to be partly due to differential nonlinearities in the position determination, differential hysteresis in the magnet iron, and imperfect matching of the magnetic fields in the three dipoles.

RESULTS

The calibration procedure outlined above was used to produce Q-value spectra by scanning event-mode tapes. Figure 5 displays the spectra for $^{98-100}$Pd and Fig. 6 displays the spectrum for ^{106}Cd. In Fig. 5(a) the three most intense peaks correspond to the $J = 0^+$, 2^+, and 4^+ states[2] of ^{98}Pd. These data represent the first measurement of the mass excess of ^{98}Pd. In Fig. 5(b) the most

TABLE II. Experimental Q values for ground and excited states for the reactions ^{96}Ru(^{16}O, $^{12-14}$C)^{100,99,98}Pd and ^{104}Pd(^{16}O, ^{14}C)^{106}Cd. The uncertainties in the last digits given in parentheses are due only to peak centroid errors and calibration errors (calibration error estimated at 10 keV, see Fig. 4).

Nucleus	J^π	Experimental Q value (MeV)	Excitation energy[a] from γ rays (MeV)	Deduced gound state mass excess (MeV)
^{98}Pd	0+	−12.537(12)	0	−81.295(12)
	2+	−13.397(13)	0.8626(5)	−81.298(13)
	4+	−14.058(16)	1.5406(7)	−81.315(16)
			adopted	−81.303(8)
^{99}Pd	$\frac{5}{2}$+	−11.738(12)	0	−82.208(12)
	$\frac{7}{2}$+	−11.971(15)	0.2640(5)	−82.218(15)
			adopted	−82.213(10)
^{100}Pd	0+	−5.604(21)	0	−85.208(21)
	2+	−5.259(19)	0.6650(5)	−85.218(19)
			adopted	−85.213(14)
^{106}Cd	0+	−10.078(11)	0	−87.139(11)
	2+	−10.648(15)	0.6327	−87.136(15)
			adopted	−87.138(9)
^{107}Cd	$\frac{5}{2}$+	−9.179(18)	0	−87.000(18)

[a]References 2 and 6.

intense peak very likely corresponds to the $J=(\frac{5}{2}+)$ ground state of ^{99}Pd. However, the centroid of this peak could be shifted to more negative Q values by any unresolved excited states of ^{99}Pd. These data provide the first direct measurement of the mass excess of ^{99}Pd, although a tabulated value[1] has been inferred from measurements of β-decay end point energies. That value implies a peak position which would lie about 100 keV to the right (more positive Q value) of the most intense peak in Fig. 5(b), and is therefore incompatible with the present measurement. In Fig. 5(c) the two

TABLE III. Summary of mass excess measurements and error estimates for $^{98-100}$Pd and ^{106}Cd.

Source of error	Mass excess error (keV) ^{98}Pd	^{99}Pd	^{100}Cd	^{106}Cd	^{107}Cd
(1) Beam energy ($\Delta E=75$ keV)	14	12	6	12	10
(2) Scattering angle ($\Delta\Theta=0.5°$)[a]	5	2	14	8	10
(3) Target thickness corrections	5	6	6	7	7
(4) Field strength dependence	6	6	6	6	6
(5) Kinematic compensation	2	5	10	3	6
(6) Amplitude dependence of position	8	8	8	8	8
(7) Centroid and calibration errors[b]	8	10	14	9	18
(8) Mass excess of target nucleus	9	9	9	5	5
Present Q value (MeV)	−12.529	−11.723	−5.599	−10.017	−9.179
	±0.020	±0.020	±0.026	±0.021	±0.027
Present mass excess (MeV)	−81.303	−82.214	−85.213	−87.138	−87.000
	±0.022	±0.022	±0.027	±0.022	±0.027
Tabulated mass excess (MeV)[c]		−82.112	−85.230	−87.131	−86.987
			±0.015	±0.006	±0.007

[a]Includes beam spot motion on target.
[b]From Table II.
[c]Reference 1.

TABLE IV. Comparison of measured mass excesses of $^{98-100}$Pd (in MeV) with values of predictions of three mass formulas. (Ref. 7.)

Nucleus	Expt.	Liran Zeldes	Jänecke Garvey Kelson	Comay Kelson
^{98}Pd	−81.303(22)	−81.02	−81.03	−81.27
^{99}Pd	−82.214(22)	−81.94	−82.05	−82.12
^{100}Pd	−85.213(27)	−84.92	−84.97	−85.16

intense peaks correspond to the $J=0^+$ and 2^+ states of ^{100}Pd. The mass excess of ^{100}Pd deduced from these data is in agreement with a previous measurement[3] using the ^{102}Pd$(p,t)^{100}$Pd reaction. In Fig. 6 the location of the $J=0^+$ and 2^+ states, as well as suggested locations for other states, are shown for the ^{104}Pd$(^{16}$O,^{14}C$)^{106}$Cd reaction. The mass excess for ^{106}Cd deduced from these data agrees with a tabulated value.[1] The small peak labeled ^{107}Cd in Fig. 6 is due to the (^{16}O,^{14}C) reaction on the 8% ^{105}Pd contaminant in the ^{104}Pd target and the mass excess deduced for this nuclide also agrees with a tabulated value. The energy resolution in these spectra is dominated by the energy loss effects in the targets.

In order to use as much of the data as possible, we have applied the known[2,6] γ-ray transition energies for $^{98-100}$Pd and ^{106}Cd to deduce additional ground state Q values from the peaks corresponding to excited states. These results are listed in Table II. The measured excitation energies generally agree with the values from γ-ray transition energies within the experimental errors. Estimates of the contribution of the various effects discussed in the previous section to the net error in the deduced mass excesses are listed in Table III. The individual components have been added in quadrature to obtain the total estimated errors.

The values determined for the mass excesses of the three Pd isotopes are compared with the predictions of three mass formulas in Table IV. The predictions of both the semiempirical shell model formula of Liran and Zeldes[7] and the Garvey-Kelson mass differences updated by Jänecke[7] are consistently 250 keV larger than the experimental values. The ensemble average of the Garvey-Kelson values by Comay and Kelson[7] is much nearer the experimental values, the average deviation being 60 keV for these three isotopes.

SUMMARY

The procedure developed for using elastic scattering to calibrate heavy ion Q-value measurements with a magnetic spectrometer is generally applicable to the wide range of mass measurements made available by heavy-ion induced transfer reactions. As has been shown by a careful analysis of errors and measurement of known masses, this procedure can yield accurate mass determinations because of the near cancellation of potentially large systematic errors. The use of elastic scattering provides a universal calibration for any few-nucleon transfer reaction.

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