# $Q$-value determination for the $^{80}$Kr(d,p)$^{81}$Kr reaction

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The ground-state $Q$ value for the $^{80}$Kr(d,p)$^{81}$Kr reaction has been determined by extrapolating to 0.0 MeV excitation the $Q$ values measured for nine excited states in $^{81}$Kr. (The ground state is not observed.) Peaks from the $^{28}$Si(d,p)$^{29}$Si reaction served as energy calibration points. A ground-state $Q$ value of 5646±4 keV was found for the $^{80}$Kr(d,p)$^{81}$Kr reaction. A ground-state mass excess for $^{80}$Kr of −77 898±7 keV was deduced using recent $^{81}$Kr ground-state mass measurements and the $^{80}$Kr(d,p)$^{81}$Kr $Q$ value from the present work.

The availability of highly isotopically enriched krypton gas has made possible many recent advances in nuclear reaction studies using krypton targets. Although the krypton isotopes have been studied with a variety of probes and reactions, precise information about the masses of many of the krypton nuclei is still lacking. The authors recently published a report[1] on a distorted-wave Born approximation (DWBA) analysis of cross section and vector analyzing power data for low-lying states in $^{81}$Kr populated by the $^{80}$Kr(d,p)$^{81}$Kr reaction using an 11 MeV vector-polarized deuteron beam. We have reexamined a number of the proton energy spectra obtained during that experiment to extract mass information. In this paper we report a $Q$ value determination for the $^{80}$Kr(d,p)$^{81}$Kr reaction and use recent measurements[2–4] of the $^{81}$Kr ground-state mass excess to deduce the ground-state mass excess of $^{80}$Kr.

The $Q$ value of the $^{80}$Kr(d,p)$^{81}$Kr reaction was previously measured in 1975 by Chao *et al.*[5] in a magnetic spectrograph. In that measurement the $Q$ values for the $^{78}$Kr(d,p)$^{79}$Kr and $^{82}$Kr(d,p)$^{83}$Kr reactions served as energy calibration references. The $Q$ values for these two (d,p) reactions were reported[6] with uncertainties of ±11 keV and ±6 keV, respectively. Chao *et al.*[5] determined a $Q$ value of 5610±15 keV for the population of the lowest-energy $^{81}$Kr state observed in the $^{80}$Kr(d,p)$^{81}$Kr reaction, compared to 5630±100 keV reported in the mass tables[6] for the ground-state $Q$ value. In 1976 Medsker[7] reinterpreted the available data on $^{81}$Kr and pointed out that the $^{80}$Kr(d,p)$^{81}$Kr $Q$ value reported by Chao *et al.* was actually the $Q$ value for the population of the first excited state. Since the $^{81}$Kr ground state has the $(1g_{9/2})^3_{7/2^+}$ configuration, it is expected to be very weakly populated in the $^{80}$Kr(d,p)$^{81}$Kr reaction. Medsker observed that a shift of 47 keV in excitation energy would bring the energy levels reported by Chao *et al.*[5] into agreement with the adopted levels in the Nuclear Data Sheets.[8] This shift implied a $^{80}$Kr(d,p)$^{81}$Kr $Q$ value of 5657±15 keV.

In the present work we have improved upon the $^{80}$Kr(d,p)$^{81}$Kr $Q$ value measurement of Chao *et al.*,[5] later corrected by Medsker,[7] by obtaining proton energy spectra with resolution better than or equivalent to those of Chao *et al.* and including, for calibration, proton peaks from (d,p) reactions with much more accurately known $Q$ values than the reference reactions used previously. A major factor contributing to the feasibility of the $Q$-value measurement reported in the present work was the use of an ion-implanted target to reduce target-related straggling. Details of the ion-implantation technique may be found elsewhere.[9] The target consisted of about 23 $\mu$g/cm$^2$ $^{80}$Kr implanted in a 90 $\mu$g/cm$^2$ carbon foil with small amounts of iron, chromium, and nickel from incidental sputtering of stainless steel, and an approximate 4 $\mu$g/cm$^2$ silicon contamination. Although peaks from contaminants and from the carbon backing foil obscured $^{81}$Kr peaks of interest at some angles, $^{29}$Si and $^{14}$C peaks in the proton spectra provided excellent $Q$- value calibration points since the masses of both the target and residual nuclei for these (d,p) reactions are well known. The typical resolution for proton energy spectra obtained with the ion-implanted $^{80}$Kr target was 25—30 keV full width at half maximum (FWHM) (see Fig. 1), contributed almost entirely by electronics and detectors, compared to 65 keV FWHM obtained using an enriched $^{80}$Kr gas cell target at ≈250 Torr with the same detectors.[1] Reaction products were detected in $E$-$\Delta E$ silicon surface-barrier detector telescopes collimated with an angular acceptance of ±1.2°.

For the purpose of this report the six proton energy spectra with maximum statistics and optimum location of the $^{29}$Si and $^{14}$C peaks relative to $^{81}$Kr peaks were reexamined. These proton spectra were measured with six different detector telescopes, three on each side of the beam at laboratory angles of 25°, 35°, and 45°. Strong proton peaks are present in each of these spectra from the $^{28}$Si(d,p)$^{29}$Si(g.s., 1273.3 keV) and $^{13}$C(d,p)$^{14}$C(g.s.) reactions along with peaks corresponding to low-lying states in $^{81}$Kr. Gaussian peak fitting was used to obtain centroids for each of these peaks. Excitation energies and uncertainties for states in $^{81}$Kr quoted in this work are taken from the Nuclear Data Sheets[10] and are listed in Table I. Association of (d,p) levels with excitation energies given in Ref. 10 are less certain for states in $^{81}$Kr above about

 

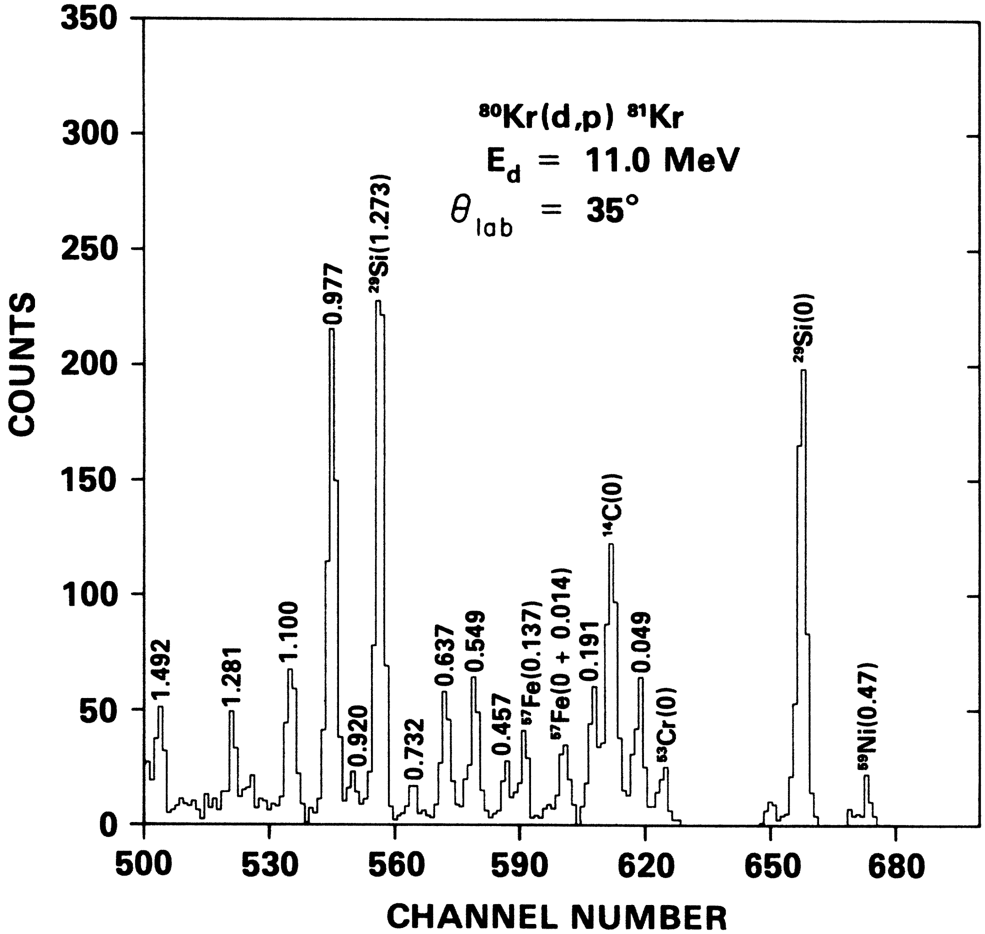


FIG. 1. A representative spectrum for the $^{80}$Kr(d,p)$^{81}$Kr reaction at $\theta_{lab}=35°$ using an ion-implanted target. The positions of peaks corresponding to states in $^{81}$Kr are indicated by their excitation energies in MeV. Peaks corresponding to states in contaminant materials or the carbon backing foil are also indicated.

TABLE I. Summary of $^{80}$Kr(d,p)$^{81}$Kr $Q$ value analyses for nine states in $^{81}$Kr from proton spectra measured at ±25°, ±35°, and ±45°.

| $^{81}$Kr excitation energy (keV) | $^{80}$Kr(d,p)$^{81}$Kr(g.s.) $Q$ value Mean value (keV) | Standard deviation (keV) |
|---|---|---|
| 49.58±0.02 | 5646.0 | 2.5 |
| 190.57±0.04 | 5646.5 | 2.6 |
| 456.69±0.02 | 5647.3 | 2.0 |
| 548.94±0.03 | 5645.8 | 2.6 |
| 636.73±0.04 | 5645.6 | 2.6 |
| 919.87±0.07[a] | 5646.8 | 4.3 |
| 976.69±0.12 | 5645.8 | 2.8 |
| 1100.19±0.06 | 5645.4 | 3.3 |
| 1280.67±0.07 | 5646.1 | 3.3 |
| 52 peaks analyzed | 5646.1 | 2.7 |

[a]At $\theta_{lab}=45°$ the yield in the 919.87 keV state is too small to reliably determine a peak centroid; therefore, only four peaks were analyzed for this state from the six spectra included in this analysis.

1.3 MeV; therefore, only peak centroids for the nine $^{81}$Kr states given in Table I were included in this analysis. A number of states in $^{59}$Ni, $^{57}$Fe, and $^{53}$Cr other than those labeled in Fig. 1 would also be populated by (d,p) reactions; however, a survey of cross sections reported in the literature shows that these weak contaminant states would, in the worst case, be expected to have a maximum peak area of 10% of the nearest $^{81}$Kr peak and hence have a minimal effect on the peak-fitting results.

The two $^{29}$Si peaks provide a reliable energy calibration since the $Q$ value for the $^{28}$Si(d,p)$^{29}$Si reaction is known to within ±0.5 keV and since the excitation energy of the state at 1.2733 MeV is accurate to ±0.1 keV.[11] Also, energy differences between these peaks caused by kinematic or target thickness effects should be negligible. The $^{14}$C peak served as a test of the energy calibration and also of corrections for differences in energy losses in the target. Since the silicon was essentially a surface contamination, while the $^{80}$Kr nuclei were implanted at a mean depth of about 15% through the backing foil, energy loss effects must be taken into consideration for the incident deuterons and exiting protons for each of the different types of nuclei in the target. We calculate that the mean energy loss caused by target effects should differ by not more than 1 keV for the three different target nuclei. The angle setting in the scattering chamber was shown to be accurate to within ±0.1° by comparing elastic scattering yields in a single detector placed at equal angles to the left and right of the beam direction. A 0.1° error in scattering angle from the assumed values would give a maximum error in the extracted proton peak energies of 1.9 keV for the $^{14}$C peak and 0.9 keV for the $^{81}$Kr peaks relative to the $^{29}$Si peak energies. Attempts to fit the spectra with various backgrounds and initial peak widths or positions demonstrated that the peak centroids could be extracted consistently with any reasonable starting assumptions to within ±10% of the peak full width at half maximum, equivalent to an uncertainty of ±2.5 to ±3.0 keV. Taking into consideration uncertainties from errors in target energy loss corrections, ±0.1° in scattering angle, and peak fitting, we calculate an uncertainty in the (d,p) $Q$ values determined in the present work of ±4.8 keV for each $^{14}$C peak and ±4.5 keV for each $^{81}$Kr peak, relative to the $Q$ value of the $^{28}$Si(d,p)$^{29}$Si reaction populating the 0.0 and 1273.3 keV states.

Using the energy calibration established by the $^{29}$Si peaks as described above, centroid energies were obtained for each of the $^{81}$Kr excited states and for the $^{14}$C ground state. The average deviation of the peak centroid energy extracted for the $^{14}$C peak from the value calculated using relativistic kinematics and mass excesses from Ref. 2 was 0.3 keV, well within the 4.8 keV uncertainty estimated above for each of the six spectra. After accounting for kinematic shifts, ground-state $Q$ values were extracted for each of the $^{81}$Kr peaks. Mean $Q$ values and standard deviations of the mean are shown in Table I for each of the nine $^{81}$Kr states analyzed. Note that peak centroids were not obtained for the 919.9 keV state at 45° because of insufficient yield in these two spectra. The mean ground-state $Q$ value extracted from the remaining 52 peaks was 5646 keV. The mean standard deviation of the 52 data points was 2.7 keV, with 90% of the points within ±4 keV, 95% within ±5 keV, and a maximum deviation from the mean of 6.2 keV. We conclude from this analysis that the ground-state $Q$ value of the $^{80}$Kr(d,p)$^{81}$Kr reaction at the 90% confidence level is 5646±4 keV.

Using the ground-state $^{80}$Kr(d,p)$^{81}$Kr $Q$ value reported above and recent measurements[2–4] of the $^{81}$Kr ground-state mass excess, we can now deduce the ground-state mass excess for $^{80}$Kr. Kouzes *et al.*[4] report a $^{81}$Kr mass excess of −77 696±6 keV. We have also reported a measurement of the $^{81}$Kr mass excess[3] in which we found a value of −77 699±8 keV, in agreement with Kouzes. The most recent mass tables[2] report a weighted mean of these two measurements, −77 697±6 keV, for the ground-state mass excess of $^{81}$Kr. Using this adjusted value and the $^{80}$Kr(d,p)$^{81}$Kr $Q$ value determined above, we deduce a ground-state mass excess for $^{80}$Kr of −77 898±7 keV, consistent with the value −77 892±8 keV reported in Ref. 2.

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