PHYSICAL REVIEW C VOLUME 35, NUMBER 4 APRIL 1987

Masses of ^{77}Kr and ^{75}Kr

D. M. Moltz
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

A. C. Betker, J. P. Sullivan, R. H. Burch, C. A. Gagliardi, and R. E. Tribble
Cyclotron Institute, Texas A&M University, College Station, Texas 77843

K. S. Toth
Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

F. T. Avignone III
Department of Physics, University of South Carolina, Columbia, South Carolina 29208
(Received 18 August 1986)

The masses of ^{77}Kr and ^{75}Kr were determined by measuring the Q values of the ^{80}Kr(^{3}He,^{6}He)^{77}Kr, ^{78}Kr(d,t)^{77}Kr, and ^{78}Kr(^{3}He,^{6}He)^{75}Kr reactions. We find that the ^{77}Kr and ^{75}Kr mass excesses are $-70.160(10)$ and $-64.231(16)$ MeV, respectively. These new results are integrated into the total scheme of mass measurements in the light rubidium and krypton isotopes. Comparisons with several mass formulae are presented.

I. INTRODUCTION

Accurate mass determinations of neutron deficient nuclei between the $1f_{7/2}$ and $1g_{9/2}$ shells are hampered by low production cross sections and complex decay schemes. The direct mass measurements[1] of the rubidium isotopes have provided a substantial base for other experiments. Unfortunately, the large uncertainties in the masses of the more neutron deficient isotopes make detailed theoretical comparisons difficult. A program was initiated several years ago to measure mass differences between light rubidium and krypton isotopes by utilizing beta-endpoint energy determinations.[2] Interpretation of these results is complicated by difficulties typical in such measurements, one of which is the lack of detailed knowledge of the decay schemes. For example, recent work[3] on ^{76}Rb decay has demonstrated that the previously accepted decay scheme was incorrect. These mass difference measurements resulted from the introduction of a simple but effective method[4,5] for precise beta-endpoint determinations. However, the ^{76}Rb-^{76}Kr mass difference yielded a mass excess for ^{76}Rb only when the mass of ^{76}Kr was determined[6] by a measurement of the Q value of the ^{78}Kr(^{4}He,^{6}He)^{76}Kr reaction. The resulting ^{76}Rb mass was anomalous when compared to the predictions of most mass formulae. The extra stability implied for this $N=39$ nucleus led us to investigate the mass of ^{75}Kr via the ^{78}Kr(^{3}He,^{6}He)^{75}Kr reaction, in order to determine whether or not this extra stability is a general feature of proton-rich $N=39$ nuclei.

In the same experiment, we measured the Q values of the ^{80}Kr(^{3}He,^{6}He)^{77}Kr and ^{82}Kr(^{3}He,^{6}He)^{79}Kr reactions. The ^{77}Kr measurement was intended to clarify the mass excess of ^{77}Kr, since recent β-γ coincidence studies[2] have called the accepted value[7–9] into question. The ^{79}Kr measurement was intended to verify our experimental technique. During the data analysis, we found that the ^{77}Kr mass excess derived from our Q-value determination disagreed with all the previous β-decay results, casting doubt on our interpretation of the observed (^{3}He,^{6}He) spectra. This interpretation required a detailed knowledge both of the level diagrams of the daughter nuclei and of the systematics of the levels populated by the (^{3}He,^{6}He) reaction in this mass region. In a subsequent experiment, we redetermined the ^{77}Kr mass excess by measuring the Q value of the ^{78}Kr(d,t)^{77}Kr reaction. This alternate measurement both confirmed the interpretation of the (^{3}He,^{6}He) results and reduced the uncertainty in the ^{77}Kr mass excess.

Section II of this paper describes the ^{78,80,82}Kr(^{3}He,^{6}He)^{75,77,79}Kr reaction studies. Section III describes the ^{78}Kr(d,t)^{77}Kr reaction study. Section IV provides some conclusions.

II. THE Kr(^{3}He,^{6}He) MEASUREMENTS

A. Experimental techniques

The ^{78,80,82}Kr(^{3}He,^{6}He)^{75,77,79}Kr reactions were all investigated with a 70-MeV ^{3}He beam from the Texas A&M University 224-cm cyclotron. Isotopically enriched gases ($>99\%$ enriched ^{78}Kr, $>90\%$ enriched ^{80}Kr, and $>90\%$ enriched ^{82}Kr) at pressures ranging from 35 to 60 Torr were held in a gas target cell having $\simeq 2$ mg/cm^2 Havar entrance and exit windows. Well-collimated reaction products at a scattering angle of $\theta_{\text{lab}}=7.25°$ were detected at the focal plane of an Enge split-pole spectrograph by a 10 cm long resistive-wire proportional counter, used as the ΔE detector, backed by a 1.0 cm $\times$ 5.0 cm $\times$ 600 μm thick silicon surface barrier detector, serving as the E detector. A 20 μm thick Kapton degrader placed between the ΔE and E detectors improved the ^{6}He energy resolution in the

E detector. Four parameters [position, ΔE, E, and time of flight (TOF) relative to the cyclotron rf pulse] were recorded on magnetic tape for each event. ^{6}He particles were identified by their characteristic ΔE, E and TOF signals. Additional experimental details may be found in Refs. 6 and 10.

The bombarding energy and scattering angle were chosen with the benefit of prior experience with (^{3}He,^{6}He) measurements in this mass region.[11] The (^{3}He,^{6}He) reaction cross section is only $\approx 2\%$ of the (^{4}He,^{6}He) cross section on any given Kr isotope. Therefore, we calibrated the spectrograph with ^{6}He particles from the ^{18}O(^{3}He,^{6}He)^{15}O reaction. We chose this calibration reaction because the ^{6}He particles from this reaction populating the 5.2 MeV doublet and the 6.18 MeV third excited state in ^{15}O bracket those from the ^{78}Kr(^{3}He,^{6}He)^{75}Kr reaction, while the ^{6}He particle rigidity in the ^{18}O(^{3}He,^{6}He)^{15}O (g.s.) reaction differs from that in the ^{82}Kr(^{3}He,^{6}He)^{79}Kr reaction by less than 1%. After the initial calibration, the enriched isotope samples of ^{82}Kr, ^{80}Kr, and ^{78}Kr were successively introduced into the gas target cell and bombarded by 21.8, 30.0, and 34.0 mC of ^{3}He^{2+} beam, respectively. An additional calibration study was performed after the Kr measurements. Finally, the evacuated gas target was irradiated by 10.0 mC of ^{3}He^{2+} beam to determine the background level due to imperfect collimation of reaction products from the Havar entrance and exit windows. Typical beam currents were between 500 and 1200 e nA.

B. The ^{82}Kr(^{3}He,^{6}He)^{79}Kr reaction

In this mass region, one might expect the angular momentum mismatch to selectively populate $L=2$ and 3 states. The level density is already quite high in these even-odd nuclei, as demonstrated by the known β-decay schemes of ^{77,79}Rb and ^{75}Rb (Refs. 12 and 13, respectively). It is, therefore, quite fortuitous that we observe primarily the negative party, $L=2,3$ states in ^{79,77,75}Kr, because these number only a few embedded in a dense region of positive parity states. The observed ^{6}He position spectrum from the ^{82}Kr(^{3}He,^{6}He)^{79}Kr reaction is shown in Fig. 1. The peak labeled (1) belongs to a $\frac{3}{2}^-$ state[12] at 0.810 MeV, and the peak labeled (2) belongs to a $\frac{3}{2}^-$ state at 0.183 MeV. The lower excitation energy (higher channel numbers) should on peak (2) belongs to a $\frac{5}{2}^-$ state at 0.147 MeV. When the measured Q values for these two peaks are corrected to account for the excitation energies and then combined, we find the ^{82}Kr(^{3}He,^{6}He)^{79}Kr ground state Q value to be $-8.822(31)$ MeV. From this, we determine the ^{79}Kr mass excess to be $-74.441(31)$ MeV, in excellent agreement with the accepted value[9] of $-74.442(6)$ MeV.

C. The ^{80}Kr(^{3}He,^{6}He)^{77}Kr reaction

Figure 2 shows the spectrum obtained from the ^{80}Kr(^{3}He,^{6}He)^{7}Kr reaction. The peaks labeled (1) and (2) belong to the $\frac{5}{2}^-$ state at 0.245 MeV and the $\frac{3}{2}^-$ state at 0.066 MeV, respectively. The four lowest levels in ^{77}Kr are at excitation energies (J^π) of 0 ($\frac{5}{2}^+$), 66 ($\frac{3}{2}^-$), 150 ($\frac{7}{2}^+$), and 245 ($\frac{5}{2}^-$) keV, respectively. The Q-value difference between peaks (1) and (2) in Fig. 2 is 192 keV making our assignment clear. The spectrum obtained with the gas cell evacuated verified that the events in channels higher than peak (2) arise in small part from imperfect collimation of reaction products from the gas cell windows and in major part from ^{79}Kr (7% ^{82}Kr isotopic contamination). Fortunately, no interferences with the ^{77}Kr peaks were observed. When the measured Q values for these peaks are combined, we find the ^{80}Kr(^{3}He,^{6}He)^{77}Kr ground state Q value to be

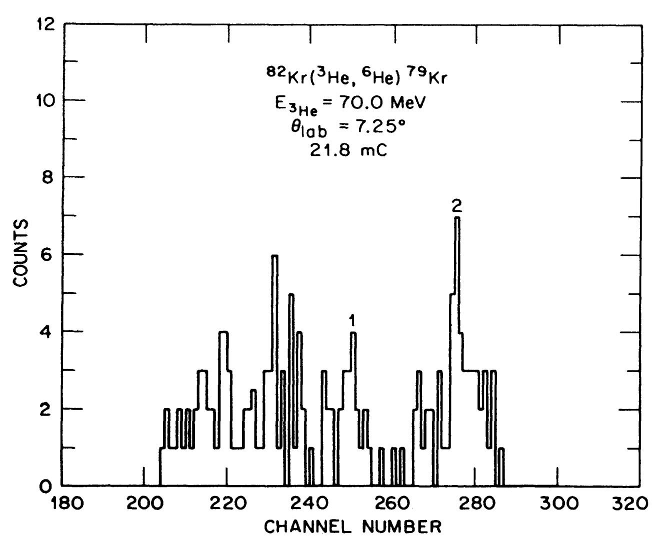

FIG. 1. The position spectrum observed in the ^{82}Kr(^{3}He,^{6}He)^{79}Kr reaction. The labeled peaks are discussed in the text.

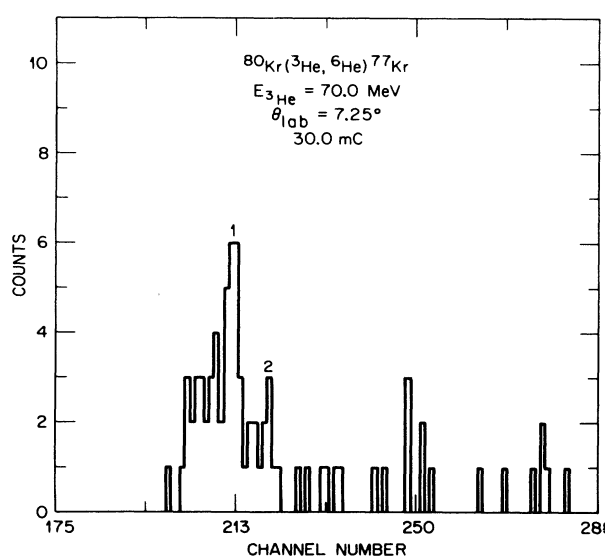

FIG. 2. The position spectrum observed in the ^{80}Kr(^{3}He,^{6}He)^{77}Kr reaction. The labeled peaks are discussed in the text.

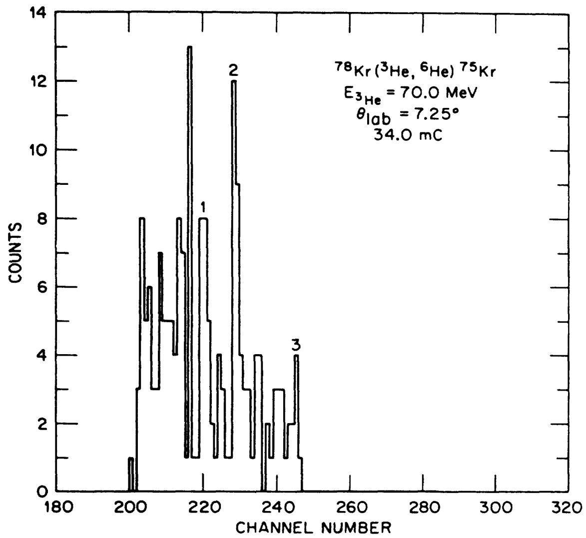

FIG. 3. The position spectrum observed in the ^{79}Kr(^{3}He,^{6}He)^{75}Kr reaction. The labeled peaks are discussed in the text.

$-10.398(24)$ MeV. From this result, we determine the ^{77}Kr mass excess to be $-70.155(25)$ MeV.

This result disagrees with the accepted value[9] of $-70.227(29)$ MeV obtained by combining data from two ^{77}Kr magnetic spectrometer β-decay endpoint measurements[7,8] with the ^{77}Br mass excess. In fact, our result agrees with one magnetic spectrometer measurement[8] of $-70.210(40)$ MeV, but it disagrees with an early measurement[7] of $-70.255(30)$ MeV. Both of these beta-endpoint measurements were recently called into question by β-γ coincidence studies[2] utilizing germanium detectors, which found a ^{77}Kr mass excess of $-70.477(42)$ MeV. This latter result was rejected by Wapstra and Audi[9] in the most recent mass compilation because it deviates significantly from the systematic trends in the mass region. These discrepancies motivated our subsequent investigation of the ^{78}Kr(d,t)^{77}Kr reaction, which is described in Sec. III. There, we determine the mass excess of ^{77}Kr to be $-70.161(11)$ MeV, in excellent agreement with our studies; it implies that the spectroscopy of the sequential β decays ^{77}Rb$\rightarrow^{77}$Kr$\rightarrow^{77}$Br is not as well understood as previously believed.

D. The ^{78}Kr(^{3}He,^{6}He)^{75}Kr reaction

Figure 3 shows the background-subtracted spectrum obtained from the ^{78}Kr(^{3}He,^{6}He)^{75}Kr reaction. Again, detailed spectroscopic information has been utilized to identify the observed peaks. The peaks labeled (1), (2), and (3) in the ^{75}Kr spectrum represent population of the $\frac{7}{2}^-$ state at 0.611 MeV, the $\frac{5}{2}^-$ state at 0.358 MeV, and the $\frac{5}{2}^+$ ground state, respectively, where the levels were identified according to Ref. 13. From the weighted Q values determined for these three states, we find the ^{78}Kr(^{3}He,^{6}He)^{75}Kr ground state Q value to be $-12.581(14)$ MeV. This result implies that the mass excess of ^{75}Kr is $-64.231(16)$ MeV.

The only prior measurement[14] of the mass of ^{75}Kr was from a plastic scintillator β-decay endpoint measurement. The measured ^{75}Kr$-^{75}$Br mass difference of 4.40(20) MeV, when combined with the mass of ^{75}Br, yields a ^{75}Kr mass excess of $-64.76(20)$ MeV. This measurement is very different from the one we report and has a large uncertainty. Furthermore, it is subject to similar systematic uncertainties as arise in the ^{77}Kr case discussed above. The value quoted by Wapstra and Audi[9] was incorrectly transcribed from a preliminary report[15] of this work. Therefore, we have no comparative value available. The excellent agreement we obtained between our measured ^{79}Kr mass excess and the accepted value, and between our two measurements of the ^{77}Kr mass excess, gives us confidence in our data analysis. Therefore, we quote $-64.231(16)$ MeV as the best available value for the mass excess of ^{75}Kr.

III. THE ^{78}Kr(d,t)^{77}Kr MEASUREMENT

The ^{78}Kr(d,t)^{77}Kr reaction was investigated with a 29.1 MeV deuteron beam from the Texas A&M University cyclotron. For this measurement, 49 Torr of 99% enriched ^{78}Kr was introduced into a gas cell similar to the one utilized for the (^{3}He,^{6}He) studies, but with a 3.4 mg/cm^2 Al entrance window. The split-pole spectrograph focused

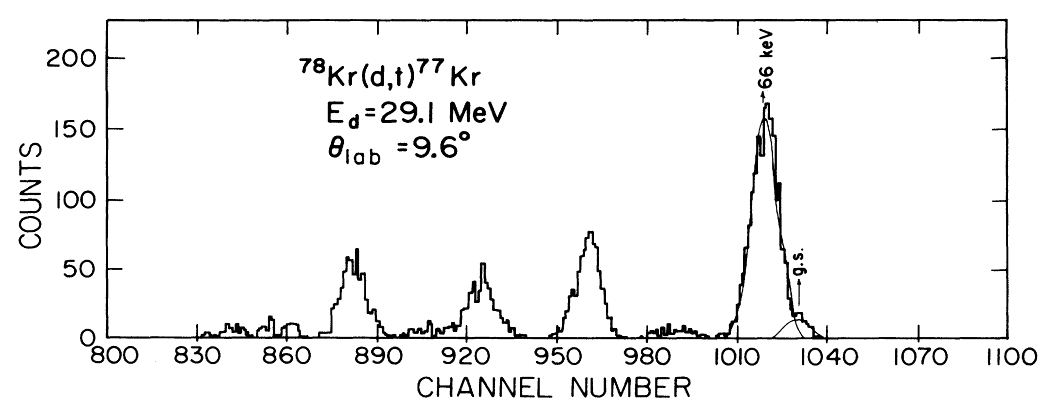

FIG. 4. The position spectrum observed in the ^{78}Kr(d,t)^{77}Kr reaction. The smooth curves show the best fit to the triton groups populating the ^{77}Kr ground and first excited states. The fit is discussed in the text.

TABLE I. A summary of the Kr mass measurements. See text for details. All values are in MeV.

	^{79}Kr	^{77}Kr	^{75}Kr
Average corrected Q value			
(^{3}He,^{6}He) reaction	−8.811(31)	−10.398(24)	−12.581(14)
(d,t) reaction		−5.804(7)	
Average mass excess	−74.441(31)	−70.160(10)	−64.231(16)
Literature	−74.442(6)[a]	−70.227(29)[a]	−64.16[b]
Adopted mass excess	−74.442(6)	−70.160(10)	−64.231(16)

[a]Reference 9.
[b]Reference 17. This result is based upon systematics.

outgoing particles at $\theta_{lab}=9.6°$ onto a 20 cm long resistive-wire proportional counter backed by a scintillator. Scattered deuterons and tritons were identified by their characteristic pulse heights in the two counters. The beam energy was determined by observing the crossover of the $^{16}O(d,d)^{16}O$ and $^{16}O(d,t)^{15}O$ reactions, using natural O_2 as the target gas, and the scattering angle was determined by simultaneously observing elastically scattered deuterons from H and C, using natural C_3H_8 as the target gas. The spectrograph focal plane was calibrated by observing tritons from the $^{22}Ne(d,t)^{21}Ne^*$ (0.351 MeV) reactions, using 99.9% enriched ^{22}Ne, and from the $^{40}Ar(d,t)^{39}Ar^*$ (1.267, 1.517, and 2.358 MeV) reactions, using natural Ar. The ^{22}Ne, ^{78}Kr, and ^{40}Ar measurements were preformed sequentially, without changing the spectrograph magnetic field. The ^{40}Ar(d,t) reaction proved to be a particularly valuable calibration because tritons populating the 2.358 MeV $J^\pi=1/2^+$ state differed in energy from those populating the ^{77}Kr 66 keV $J^\pi=3/2^-$ state by only 225 keV.

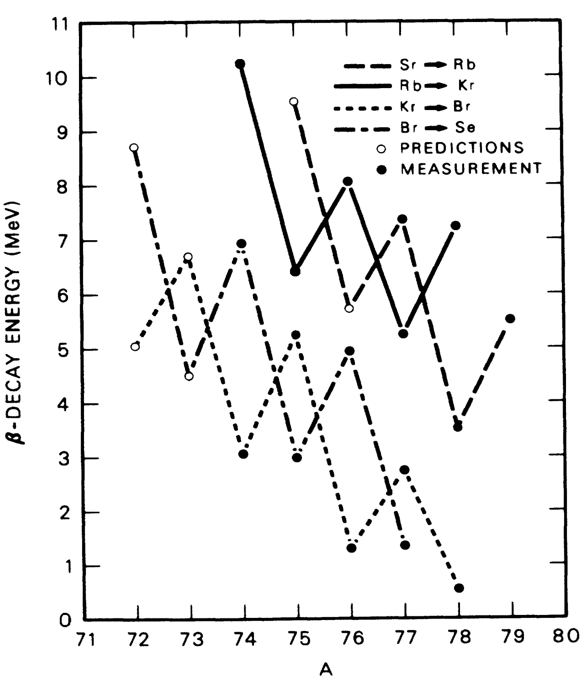

FIG. 5. Beta-decay energy systematics for light strontium, rubidium, krypton, and bromine isotopes. Predictions are taken from Ref. 9.

Figure 4 shows the triton position spectrum obtained in the $^{78}Kr(d,t)^{77}Kr$ reaction. The smooth curves are the best Gaussian fit to the triton groups populating the unresolved ground and the first excited states. This fit required the two peaks to have the correct 66 keV separation energy and the same width. the 65 keV full width at half maximum (FWHM) resolution extracted from this fit is consistent with the ^{22}Ne and ^{40}Ar studies, where all peaks are cleanly resolved, and the 10:1 relative yield of the first excited state to the ground state is consistent with that seen in a previous 16 MeV $^{78}Kr(\vec{d},t)^{77}Kr$ reaction study.[16] From this fit, we find that the ground state Q value for the $^{78}Kr(d,t)^{77}Kr$ reactions is −5.804(7) MeV, and that the ^{77}Kr mass excess is −70.161(11) MeV. It should be noted that the dominant contributions to the

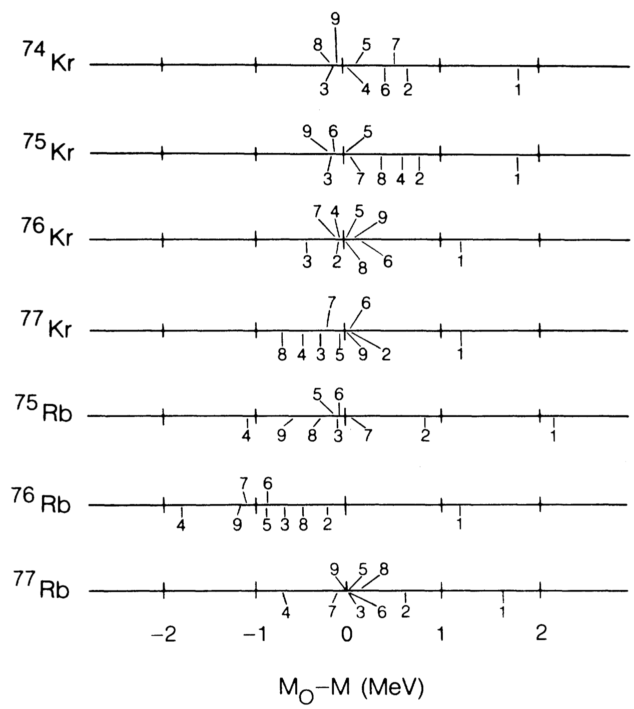

FIG. 6. Mass formulae comparisons for several rubidium and krypton isotopes. All predictions are taken from Ref. 18 unless noted, and correspond to (1) Myers, (2) Groote *et al.*, (3) Seeger and Howard, (4) Liran and Zeldes, (5) Janecke and Garvey-Kelson, (6) Comay and Kelson, (7) Janecke and Eynon, (8) Möller and Nix (Ref. 19), and (9) Monohan and Serduke (Ref. 20).

uncertainty in this result come from the 5 and 8 keV uncertainties in the accepted ^{39}Ar and ^{78}Kr mass excesses, respectively.

This result is in excellent agreement with our result from the ^{80}Kr(^{3}He,^{6}He)^{77}Kr reaction. Therefore, we combine the two results to obtain $-70.160(10)$ MeV for the ^{77}Kr mass excess. This new ^{77}Kr mass excess permits us to recalculate the ^{77}Rb mass excess, using the previously reported[2] ^{77}Rb$-$^{77}Kr mass difference. We find the ^{77}Rb mass excess is $-64.888(28)$ MeV. This result is 200 keV more negative than the result[1] of a direct mass measurement [$-65.100(105)$ MeV]. At this time, it is not clear whether or not this two standard deviation discrepancy is related to our lack of understanding of the mass-77 sequential β-decays discussed in Sec. II C.

IV. CONCLUSIONS

Table I contains a summary of our results. The quoted Q values have been corrected for different recoil energy losses and include, where applicable, results from reactions leading to multiple states as discussed previously. Reference 17 has been utilized for reasons discussed in the ^{78}Kr(^{3}He,^{6}He)^{75}Kr section. These results have been integrated into the beta-decay energy systems depicted in Fig. 5. If one compares some of these Rb and Kr masses used in Fig. 5 with the theoretical predictions[18–21] illustrated in Fig. 6, we observe that the recursive mass formulae (numbers 5, 6, and 7 in Fig. 6) give values consistently closer to the measured value if the ^{76}Rb mass is disregarded. Most of the mass formulae predict the Kr masses rather well, but tend to miss the Rb masses.

Since the ^{75}Kr mass is consistent with the other Kr isotopes, we must conclude that the $N=39$ configuration is not especially favored and that ^{76}Rb must represent an unusual case. It is now recognized[3,22] that ^{76}Rb is one of the most deformed nuclei known. If one considers the mass predictions depicted in Fig. 6 in a sequential manner from ^{77}Rb to ^{75}Rb, the formula which comes closest to the experimental results is that of Möller-Nix.[21] We attribute this to their inclusion of the effects of strong prolate deformation. There may exist, however, other effects which serve to make ^{76}Rb a unique case perhaps warranting additional study. This could include remeasurement of the β^{+} spectrum coincident with the dominant 2571 keV transition.

Although our understanding of the rudimentary nuclear physics has been furthered by these mass determinations, probably more questions have been raised than have been answered.

ACKNOWLEDGMENTS

We wish to thank the staff at the Texas A&M University cyclotron for their help in this work. The work at Texas A&M is supported in part by the U.S. Department of Energy and the Robert A. Welch Foundation. Oak Ridge National Laboratory is operated by Martin Marietta Energy Systems, Inc. for the U.S. Department of Energy under Contract DE-AC05-840R21400. This work was supported in part by the U.S. Department of Energy under Contract DE-AC03-76SF00098.

[1]G. Audi, M. Epherre, C. Thibault, A. H. Wapstra, and K. Bos, Nucl. Phys. **A378**, 443 (1982).
[2]D. M. Moltz, K. S. Toth, F. T. Avignone III, H. Noma, B. G. Ritchie, and B. D. Kern, Phys. Lett. **113B**, 16 (1982).
[3]D. M. Moltz, K. S. Toth, F. T. Avignone III, H. Noma, B. D. Kern, R. E. Tribble, and J. P. Sullivan, Nucl. Phys. **A427**, 317 (1984).
[4]F. T. Avignone III H. Noma, D. M. Moltz, and K. S. Toth, Nucl. Instrum. Methods **189**, 453 (1981).
[5]F. T. Avignone III, L. P. Hopkins, and Z. D. Greenwood, Nucl. Sci. Eng. **72**, 216 (1979).
[6]D. M. Moltz, K. S. Toth, R. E. Tribble, R. E. Neese, and J. P. Sullivan, Phys. Rev. C **26**, 1914 (1982).
[7]S. Thulin, Ark. Fys. **9**, 137 (1955).
[8]K. A. Baskova, S. S. Vasil'ev, M. A. Mokhsen, T. V. Chugai, and L. Ya. Shavtvalov, Izv. Akad. Nauk SSR (Ser. Fiz.) **37**, 73 (1973).
[9]A. H. Wapstra and G. Audi, Nucl. Phys. **A432**, 1 (1985).
[10]C. J. Woodward, R. E. Tribble, and D. M. Tanner, Phys. Rev. C **27**, 27 (1983).
[11]R. C. Pardo, E. Kashy, W. Benenson, and L. W. Robinson, Phys. Rev. C **18**, 1249 (1978).
[12]*Table of Isotopes,* 7th ed., edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978).
[13]B. D. Kern, K. S. Toth, D. M. Moltz, J. Lin, F. T. Avignone III, H. Noma, and G. A. Leander, Phys. Rev. C **28**, 2168 (1983).
[14]E. Roeckl, D. Lode, and W. Pessara, Z. Phys. **266**, 123 (1974).
[15]D. M. Moltz, J. P. Sullivan, C. A. Gagliardi, R. E. Tribble, K. S. Toth, and F. T. Avignon III, Proceedings of the 7th International Conference on Atomic Masses and Fundamental Constants (AMCO-7), Darmstadt-Seeheim, FRG, 1984, p. 112 (unpublished).
[16]R. R. Cadmus, Jr., T. B. Clegg, E. J. Ludwig, and S. A. Wender, Nucl. Phys. **A319**, 165 (1979).
[17]A. H. Wapstra and K. Bos, At. Data Nucl. Data Tables **19**, 177 (1977).
[18]S. Maripuu, special ed., At. Data Nucl. Data Tables **17**, 411 (1976).
[19]P. Möller and J. R. Nix, At. Data Nucl. Data Tables **26**, 165 (1981).
[20]P. E. Haustein (unpublished).
[21]P. Möller and J. R. Nix, Nucl. Phys. **A361**, 117 (1981).
[22]C. J. Lister, B. J. Varley, H. G. Price, and J. W. Olness, Phys. Rev. Lett. **49**, 308 (1982).