PRECISION Q-VALUE DETERMINATIONS FOR NEUTRON-RICH RUBIDIUM ISOTOPES AT TRISTAN

D. S. Brenner, M. K. Martel and A. Aprahamian
Clark University, Worcester, Massachusetts, USA

R. E. Chrien, R. L. Gill, G. M. Gowdy, H. I. Liou, M. Shmid and M. L. Stelts
Brookhaven National Laboratory, Upton, New York, USA

F. K. Wohn
Iowa State University, Ames, Iowa, USA

C. Chung
University of Maryland, College Park, Maryland, USA

D. M. Rehfield
McGill University/Vanier College, Montreal, Quebec, Canada

Abstract

Beta-ray end-point energies for Rb fission products were measured at the TRISTAN on-line mass separator using an intrinsic Ge β spectrometer. Coincidence measurements were used to establish feeding relationships and to verify level schemes in daughter nuclides. Q_β values are reported for ^{88,94,96,98}Rb and compared with results from other experiments and with predictions of mass formulae.

1. Introduction

The determination of accurate atomic masses in neutron-rich nuclei is necessary for further refinement of mass formulae which are used to predict properties of unknown nuclides far from stability. Improvement in the accuracy of these equations is important since they are used in calculations of both fundamental and practical significance. For example, improved accuracy in mass equations would aid in refining reactor decay-heat predictions, searches for delayed neutron emitters and in improving calculations of the competition between neutron capture and β decay on rapid time scales. The first two items are important for efficient and safe design of future fission reactors;[1)] the third relates to theories of astrophysical significance.[2,3)]

Masses of unstable neutron-rich nuclides traditionally have been determined by β-ray end-point measurements. If the excitation energy of the populated level or levels is known, then the mass difference between the two members of the isobaric chain is determined. Normally, plastic scintillators are used as β detectors and the β-ray singles spectrum and/or beta spectra in coincidence with γ-deexcitation of daughter nuclei are recorded. Recently, hyperpure intrinsic Ge detectors have been introduced. These offer the potential for determining end-point energies with higher precision than is possible with scintillation detectors, thus permitting more precise mass determinations for nuclides which undergo β decay.[4,5)]

For stable isotopes high resolution mass spectroscopy has been used to directly measure mass differences. Recently, Epherre et al.[6)] have used a clever adaptation of this technique to study radioactive nuclides far from stability. Using the on-line mass separator ISOLDE at CERN they made precision direct mass measurements of $^{74-79}$Rb, $^{90-99}$Rb and numerous Cs isotopes. In some instances their results were found to be at variance with those determined by Q_β measurements.[7-9)] In the case of Cs isotopes the discrepancies between the two types of measurements were found to result from a significant error in the value of a reference mass used in calibrating the direct mass experiments.[10)] No such systematic error affected the Rb direct mass measurements.

The recent Q_β work on very neutron-rich Rb isotopes comes from three groups. Keyser et al.[11)] have determined Q values for $^{92-98}$Rb using a plastic scintillation counter-telescope/Ge(Li) spectrometer at the mass separators LOHENGRIN and OSTIS located at the high flux reactor of the Institute Laue-Langevin. Decker et al.[9)] have also reported Q_β values from OSTIS measured using an intrinsic Ge β detector. The results of Peuser et al.[8)] were obtained using a plastic counter-telescope at the Mainz reactor. There are major discrepancies among the various Q_β measurements (>1 MeV in some cases) as well as between some of the Q_β results and the direct mass measurements. The values reported by Keyser et al. are in agreement with the direct mass data within stated errors which, however, become quite large far from stability: ^{98}Rb, ±300 keV Q_β method; ±155 keV direct mass method. In view of the somewhat unsettled situation for the neutron-rich Rb isotopes, we decided to begin our Q_β measurement program at TRISTAN in this mass region.

2. Experimental Methods

2.1 The TRISTAN Facility

The TRISTAN on-line mass separator at the High Flux Beam Reactor, Brookhaven National Laboratory became operational late in 1980. Detailed information about the capabilities of the separator and associated data acquisition/analysis systems can be found in references[12,13)] and citations therein. Initial operations have used a positive ion surface ionization source[14)] which contains ∿5g of enriched ^{235}U in a graphite cloth matrix. The source is positioned in a neutron beam flux of $\sim 1.5\text{x}10^{10}$ n/cm^2·sec external to the reactor containment shield. Primary beams of alkalai metals (Rb,Cs) and alkaline earths (Sr,Ba) are extracted, mass separated by a 90° magnetic sector and deposited on a movable tape. A tape transport mechanism permits timed movements of the source deposit relative to detectors positioned at the point of deposit (parent port) or at a secondary station (daughter port). Proper choice of time sequencing permits selective enhancement of various members of an isobaric decay chain. Because of massive shielding of the ion source and primary separator components a low background is maintained at the counting stations.

2.2 Beta-Ray End-Point Measurements

We have developed a system for Q-value measurements similar in design to that reported by Wünsch *et al.*4,5) in which a hyperpure Ge detector is used to measure β spectra. Our detector which has a surface area of 250 mm^2 and 10 mm active thickness is mounted in a cryostat equipped with a 12 μm titanium entrance window. The detector assembly is integrally mounted into the vacuum system of the TRISTAN moving tape collector so that the source-to-detector distance is 15 mm. Determination of energy loss for β rays in the detector window and dead layer was made using conversion electron sources. The γ-ray sensitivity of the β detector is employed as a means for energy calibration using the many well known high-energy lines of ^{90}Rb measured on-line at the separator.15) To minimize systematic errors in β-ray end-point energies due to accidental summing pulse pile-up rejection circuitry was used and counting rates were kept below 3 kHz.

Additional information is provided by measuring γ-ray spectra in coincidence with β rays using a 20% Ge(Li) detector located on the opposite side of the source. β-γ coincidence measurements are necessary when there is more than a single β-branch of significant intensity; when Q_β for decay of the daughter isotope is comparable or greater than Q_β for the nuclide of interest; or when β decay does not occur between ground states. We record event-mode (β-γ-t) coincidence data which is sorted off-line into spectra for various β branches. This complication has a compensating benefit, however, in that it provides data on alternative paths for checking derived Q_β values. It also provides a means for testing the validity of the decay scheme.

Pile-up rejection circuitry and a constant-fraction timing coincidence system are interfaced with a digitally-stabilized data acquisition system based on a PDP-11/20 computer fed by a CAMAC driver. The CAMAC incorporates a microprogrammed branch driver which can multiplex up to eight separate data channel inputs. Coincidence data are event-mode recorded (β-γ-t) on magnetic tape. An off-line PDP-11/34 computer is used for tape scanning, plotting and data analysis. Of particular interest for these studies is an interactive computer code, BDK, for analysis of β-ray spectra which has been described in detail by Rehfield.16) In most cases reported here this code was used to linearize data in the high energy region of the β spectrum, thus permitting accurate determination of the end point.

3. Results and Discussion

Experimental Q_β values for some neutron-rich Rb isotopes are found in Table 1. In addition to the results of the present study we include for comparison values reported by others using intrinsic Ge detectors,9,10,17) plastic scintillation counter-telescopes8,11) and a mass spectrometer.6) The mass spectrometer results have been adjusted by Keyser *et al.*11) to permit direct comparison with Q_β measurements. Each of the Rb isotopes will be discussed in turn.

3.1 ^{88}Rb

In Fig. 1 we show experimental data and a Fermi-Kurie fit to the end-point region of the ^{88}Rb β spectrum as measured at TRISTAN using an intrinsic Ge detector. We determine an end-point energy of 5313±5 keV in excellent agreement with the McGill and OSTIS results (Table 1). It should be

Table 1. Q_β Values for Rb Isotopes

	^{88}Rb	^{94}Rb	^{96}Rb	^{98}Rb
TRISTAN (Ge)a)	5313±5	10,353±100	11,547±100	12,343±150
McGill (Ge)b)	5310±10	-	-	-
OSTIS (Ge)	5317±3c)	10,304±30d)	>11,303±250d)	-
LOHENGRIN/OSTIS (plastic)e)	-	10,185±150	11,670±130	12,230±300
Mainz (plastic)f)	-	-	10,800±220	11,200±110
ISOLDE (direct)g)	-	10,125±50 (10,361±50)	11,735±85	12,405±155

a) this work.
b) ref. 17).
c) ref. 10).
d) ref. 9).
e) ref. 11).
f) ref. 8).
g) ref. 6 as adjusted in ref. 11).

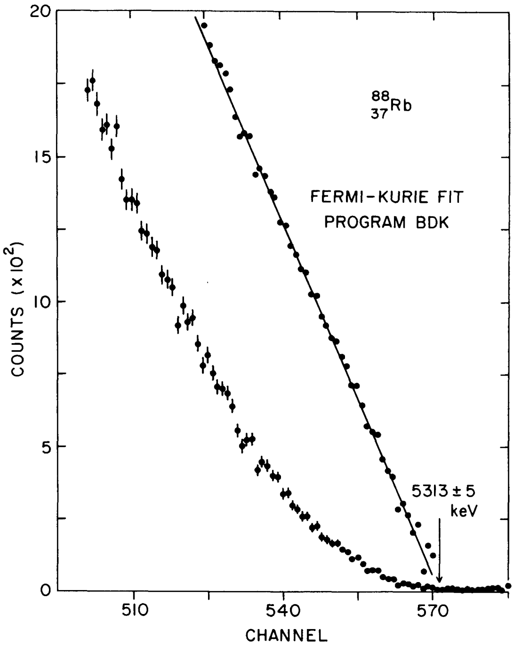

Fig. 1 The β spectrum and Fermi-Kurie fit in the end-point region for ^{88}Rb decay.

noted that the very high precision of Ge β-detector measurements for ^{88}Rb is made possible by a number of favorable circumstances including a high fission yield, a convenient half life, a dominant ground state β-branch to stable ^{88}Sr, and the availability of well-known calibration rays from ^{90}Rb which bracket the end-point region.

3.2 ^{94}Rb

There exist discrepancies among Q_β values reported for decay of ^{94}Rb which may be due to the existence of an as yet uncharacterized isomeric state in ^{94}Rb. Epherre et al.$^{6)}$ report a variation in the mass of ^{94}Rb with temperature of the ionizing surface in their on-line mass spectrometer at ISOLDE. They surmised that the ^{94}Rb isomer was approximately 200 keV less bound than the ground state and that its half-life was somewhat shorter than 2.7s, the ground state value. No direct observation of this isomer has been reported, however. Keyser et al.$^{11)}$ derived Q_β values of 10,125±50 and 10,361±50 keV from the ISOLDE results for decay of the ground and isomeric states, respectively. They also made an independent measurement with a scintillation counter-telescope at LOHENGRIN/OSTIS and report Q_β=10,185±150 keV, overlapping within combined experimental precision both ground and isomeric results determined by direct mass measurements. Decker et al.$^{9)}$ have also reported a Q_β value for ^{94}Rb measured at OSTIS using an intrinsic Ge detector. Their result, 10,304±30 keV agrees with the direct mass result for the isomeric state but is outside reported error for that of the ground state.

In our experiments at TRISTAN using an intrinsic Ge β-ray/Ge(Li) γ-ray spectrometer, ^{94}Rb activity was collected for a period of 5.0s at the parent port during which data acquisition was operational, followed by a 0.5s interval in which the ion beam was deflected, counting was inhibited and the tape was moved so that the activity spot was in a shielded location. This duty cycle served to enhance ^{94}Rb activity recording relative to longer-lived daughter products.

Analysis of the β-γ coincidence spectra confirms the result of others that the most energetic β branch feeds a level at 2414 keV in ^{94}Sr. We derive an endpoint energy of 7939±100 keV which implies Q_β=10,353±100 keV. Our result is in excellent agreement with Decker et al. and the ISOLDE isomeric value. It is barely within combined errors of the Keyser et al. result and outside limits for the direct mass ground state. It is perhaps possible that the Ge experiments are observing the decay of a different species than was seen in the plastic and lower temperature direct measurements. Better understanding of this discrepancy awaits elucidation of the isomer situation in ^{94}Rb.

3.3 ^{96}Rb

In a similar fashion we have determined Q_β for ^{96}Rb. Because of shorter half lives a 1.0s (collect, count)/0.3s (tape move) cycle was used to enhance ^{96}Rb data collection relative to daughter activities. The end-point energy for the β-branch feeding the 1628 keV level in ^{96}Sr was determined to be 9919±100 keV yielding a Q_β value of 11,547±100 keV. This is in good agreement with Keyser et al. and falls slightly outside the stated error limit of the ISOLDE result. The Mainz group$^{8)}$ reports Q_β= 10,800±220 keV substantially below all other results.

3.4 ^{98}Rb

In the case of ^{98}Rb decay there is an important disagreement between the decay scheme of Peuser et al.$^{8)}$ and that of Jung.$^{18)}$ The Mainz group reported β feeding to a level at 2606 keV in ^{98}Sr which deexcited by a 2172-289-145 keV cascade **to the** ground state. Jung, however, placed the 2172 keV γ ray as

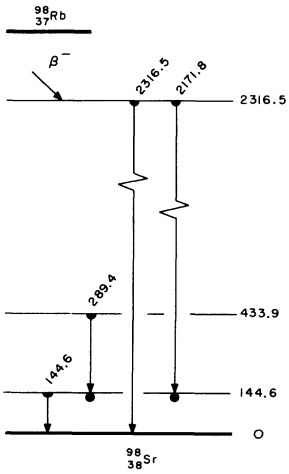

Fig. 2 Partial decay scheme for ^{98}Rb.

deexciting a level at 2316 keV via a 2316-144 keV cascade (Fig. 2). Since the most energetic β branch is seen in coincidence with the 2172 keV γ ray it was necessary to determine which of the above schemes was correct. γ-γ coincidence spectra recorded simultaneously with our β-γ measurements clearly support the scheme reported by Jung.

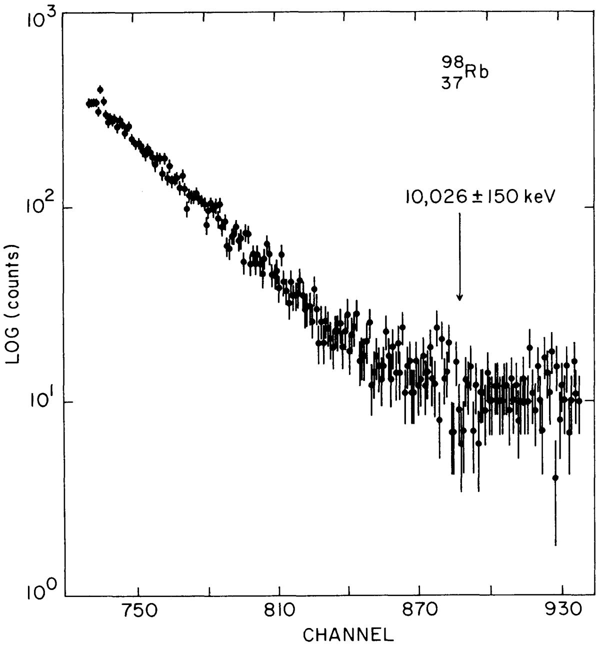

Fig. 3 The β spectrum end-point region for ^{98}Rb decay.

Figure 3 shows the end-point region of the ^{98}Rb β spectrum. At very high β energies uncertainties in our detector response function prevented accurate Fermi-Kurie analysis using the computer code BDK. Fortunately, a simple semi-logarithmic plot served to linearize the data in the end-point region and permit the extraction of a precise end point. We arrive at an end-point energy of 10,026±150 keV yielding Q_β=12,343±150 keV. Our result is in excellent agreement with the direct mass measurement and the somewhat less precise plastic result of Keyser et al. Again the Mainz value falls far lower than all others.

3.5 Comparison with Mass Formulae

There appears to be substantial agreement among experimenters for Q_β values of very neutron rich even-A Rb nuclides. The situation is not quite as clear for the odd-A isotopes largely due to decay scheme uncertainties. In general, Q_β measurements strongly support the mass excess results of Epherre et al. out through ^{98}Rb, the most neutron excess specie studied to date by β decay. Thus the Rb isotopes provide a well founded basis for comparison with predictions of mass formulae. In Fig. 4 the differences between calculated and experimental mass excess values for Rb isotopes are plotted. The calculated results are those tabulated by Maripuu[19] and represent a spectrum of different types of mass formulae. It is clear that for the neutron-rich isotopes beyond ^{94}Rb there are systematic errors, often quite large, in the calculated mass excesses.

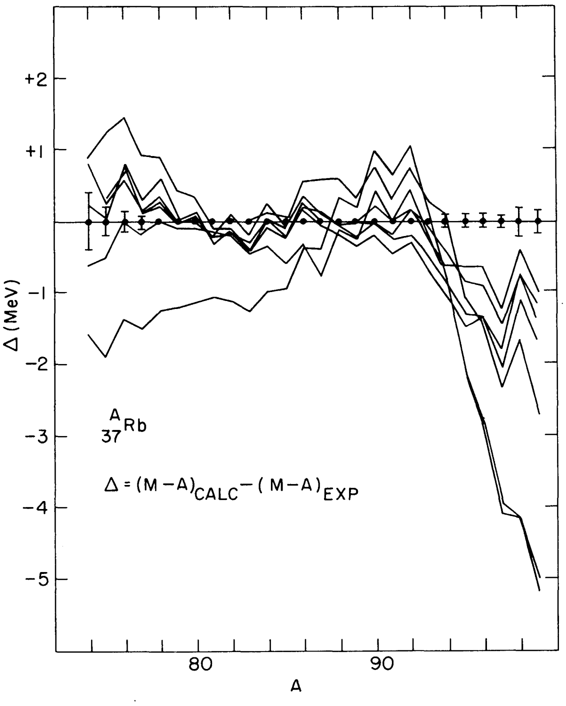

Fig. 4 Comparison of experimental and calculated mass excesses for Rb isotopes.

It is of extreme importance to extend our knowledge of other isotopic chains far away from stability in order to see if similar deviations occur, especially in the fission product region. Without these data, calculations which are based on the predictions of mass formulae for very neutron rich nuclides, may be unreliable.

References

1) C. W. Reich, Proceedings of the Isotope Separator On-Line Workshop, Brookhaven National Laboratory, R. E. Chrien, Ed., report BNL 50847 (1978).
2) T. Kodama and K. Takahashi, Nucl. Phys. A239, 489 (1975).
3) M. Arnould, Atomic Masses and Fundamental Constants 6, J. A. Nolen, Jr. and W. Benenson, Eds., Plenum Press, New York and London, 375 (1979).
4) K. D. Wünsch, R. Decker, H. Wollnik, J. Münzel, G. Siegert, G. Jung and E. Koglin, Z. Physik A288, 105 (1978).
5) K. D. Wünsch, Nucl. Instr. & Meth. 155, 347 (1978).
6) M. Epherre, G. Audi, C. Thibault, R. Klapisch, G. Huber, F. Touchard and H. Wollnik, Phys. Rev. C19, 1504 (1979).
7) R. Stippler, F. Münnich, H. Schrader, J. P. Bocquet, M. Asghar, G. Siegert, R. Decker, B. Pfeiffer, H. Wollnik, E. Monnaud and F. Schussler, Z. Physik A284, 95 (1978).
8) P. Peuser, H. Otto, N. Kaffrell, G. Nyman and E. Roeckl, Nucl. Phys. A332, 96 (1979).

9) R. Decker, K. D. Wünsch, H. Wollnik, E. Koglin, G. Siegert and G. Jung, Z. Physik A294, 35 (1980).

10) H. Wollnik, F. Blönnigen, D. Rehfield, G. Jung, B. Pfeiffer and E. Koglin, Atomic Masses and Fundamental Constants 6, J. A. Nolen, Jr. and W. Benenson, Eds., Plenum Press, New York and London, 465 (1979).

11) U. Keyser, H. Berg, F. Münnich, B. Pahlmann, R. Decker and B. Pfeiffer, Atomic Masses and Fundamental Constants 6, J. A. Nolen, Jr. and W. Benenson, Eds., Plenum Press, New York and London, 443 (1979).

12) D. S. Brenner, R. E. Chrien, R. L. Gill, M. L. Stelts, J. C. Hill and F. K. Wohn, Proceedings of the International Symposium on Future Directions in Studies of Nuclei far from Stability, J. H. Hamilton, E. H. Spejewski, C. R. Bingham and E. F. Zganjar, Eds., North-Holland, Amsterdam, New York and Oxford, 389 (1980).

13) R. L. Gill, M. L. Stelts, R. E. Chrien, V. Manzella, H. I. Liou and S. Shostak, Proceedings of the EMIS-10 Conference, Nucl. Instr. & Meth. (to be published, 1981).

14) M. Shmid, R. L. Gill, G. M. Gowdy and C. Chung, Bull. Am. Phys. Soc. 26, 594 (1981).

15) H. Huang, B. P. Pathak, R. Iafigliola, L. Lessard and J. K. P. Lee, Z. Physik A282, 285 (1977).

16) D. M. Rehfield, Nucl. Instr. & Meth. 157, 351 (1978).

17) D. M. Rehfield, L. Lessard, L. M. Nikkinen, R. B. Moore and J. K. P. Lee, private communication.

18) G. Jung, Ph.D. thesis, University of Giessen, 1980, unpublished.

19) S. Maripuu, Atomic Data and Nuclear Data Tables 17, i (1976).