PHYSICAL REVIEW C **82**, 024603 (2010)

Q value for the double-β decay of ^{136}Xe

P. M. McCowan and R. C. Barber
Department of Physics and Astronomy, University of Manitoba, Winnipeg MB R3T 2N2, Canada

(Received 12 May 2010; published 3 August 2010)

The high-resolution, deflection-type mass spectrometer, Manitoba II, has been used to determine directly the mass difference ^{136}Xe$-^{136}$Ba to be 2639.6 (0.6) μu, giving $Q_{\beta\beta} = 2458.7$ (0.6) keV.

DOI: 10.1103/PhysRevC.82.024603 PACS number(s): 23.40.−s, 21.10.Dr, 27.60.+j

I. INTRODUCTION

The high-resolution mass spectrometer at the University of Manitoba ("Manitoba II") has been used for the precise determination of atomic mass differences in a long-term program, predominantly in the upper half of the mass table. Recent studies have been directed toward mass differences that are of particular interest, such as those giving the energy available for double-β decay.

The double-β decay mode, in which two neutrinos and two electrons are simultaneously emitted, was proposed by Maria Goeppert-Mayer [1] in 1935 and has now been observed for at least ten nuclides. An alternate mode, in which only two electrons are emitted, was proposed by Wolfgang Furry [2] in 1939 and is of special interest. Such a decay would violate the lepton-number conservation rule and would imply physics beyond the standard model. If the neutrino mass were nonzero and if the neutrino were its own antiparticle, this mode of decay could occur. Accordingly, several studies have been undertaken. In the favorable case of ^{76}Ge, we have given a precise value for the energy available for the decay [3], a value whose precision is comparable to the energy resolution of the detection system. The current interest in the double-β decay of ^{136}Xe has prompted the direct measurement of the mass difference that is reported here.

II. EXPERIMENTAL DETAILS

A. The mass spectrometer

The Manitoba II mass spectrometer [4–6] at the University of Manitoba is a deflection-type, second-order, double-focusing instrument. It has been operated routinely at a resolving power, $M/\Delta M$, of 2×10^5 and has been used extensively for precise atomic-mass determinations of stable nuclides, with a precision usually in the range of 2–5 parts in 10^9 of the mass.

The mass spectrometer consists of a nominally 94.65° cylindrical electrostatic analyzer (ESA), having a radius $r_e = 100.0$ cm, followed by a 90° uniform magnetic field with a nominal radius of 62.74 cm. The geometry is one of several arrangements proposed by Hintenberger and König [7] that produces a focus, corrected for image aberrations to second order, for ions that diverge in angle in the plane of the instrument and in velocity from the nominal median velocity. Although these calculated geometries did not include the effects of fringe fields, later improved calculations showed that for this instrument the image aberrations remained small. As discussed here, this particular geometry has the important feature that, for a particular energy, ions are brought to an intermediate real focus 17.63 cm outside the exit boundary of the electrostatic analyzer.

Although the geometry of the instrument has not been altered, several modifications and improvements have been made in the course of its operation. The replacement of the magnet power supply and the magnet coils was described by Hykawy *et al.* [3]. The ion source used in this work was of the type reported previously by Barber *et al.* [4] with a gas inlet added so as to permit the introduction of the gas sample into the heated oven. The detector used in the present work is one in which the ions strike an aluminum conversion plate, with the secondary electrons accelerated to and detected by a continuous dynode electron multiplier (channeltron). The voltage supply for the electrostatic analyzer is now based on a pair of highly stable electronic supplies (Fluke 5440B direct volts calibrator) and a pair of matched, isolated voltage supplies described by Barillari *et al.* [8].

B. Peak matching

A schematic diagram of the mass spectrometer, showing the control and data acquisition system, is given in Fig. 1. A mass spectral peak is obtained by sweeping the ion beam across the collector slit. This is done by generating a small sawtooth magnetic field with a pair of Helmholtz coils located in the drift space between the magnetic field and the detector. The master trigger starts a sweep of the live display oscilloscope and signal averager, along with a sawtooth current in the coils. Since these are synchronized, a peak is observed on the display and is also stored in the signal averager.

Mass differences between the two members of a mass doublet are determined by the application of the Swann-Bleakney [9,10] theorem. For any combination of electric and magnetic fields, an ion of mass M may define a path through the fields. Then, if all of the magnetic fields are held constant, and if all of the electric fields, E_i, are changed to E_i', a second ion of mass M' will follow the identical path, provided that

$$M\,E_i = M'E_i'. \tag{1}$$

Assuming that the field E, which the ion encounters, is produced by a related applied voltage, V, then we have

$$MV = M'V' = M'(V + \Delta V) \tag{2}$$

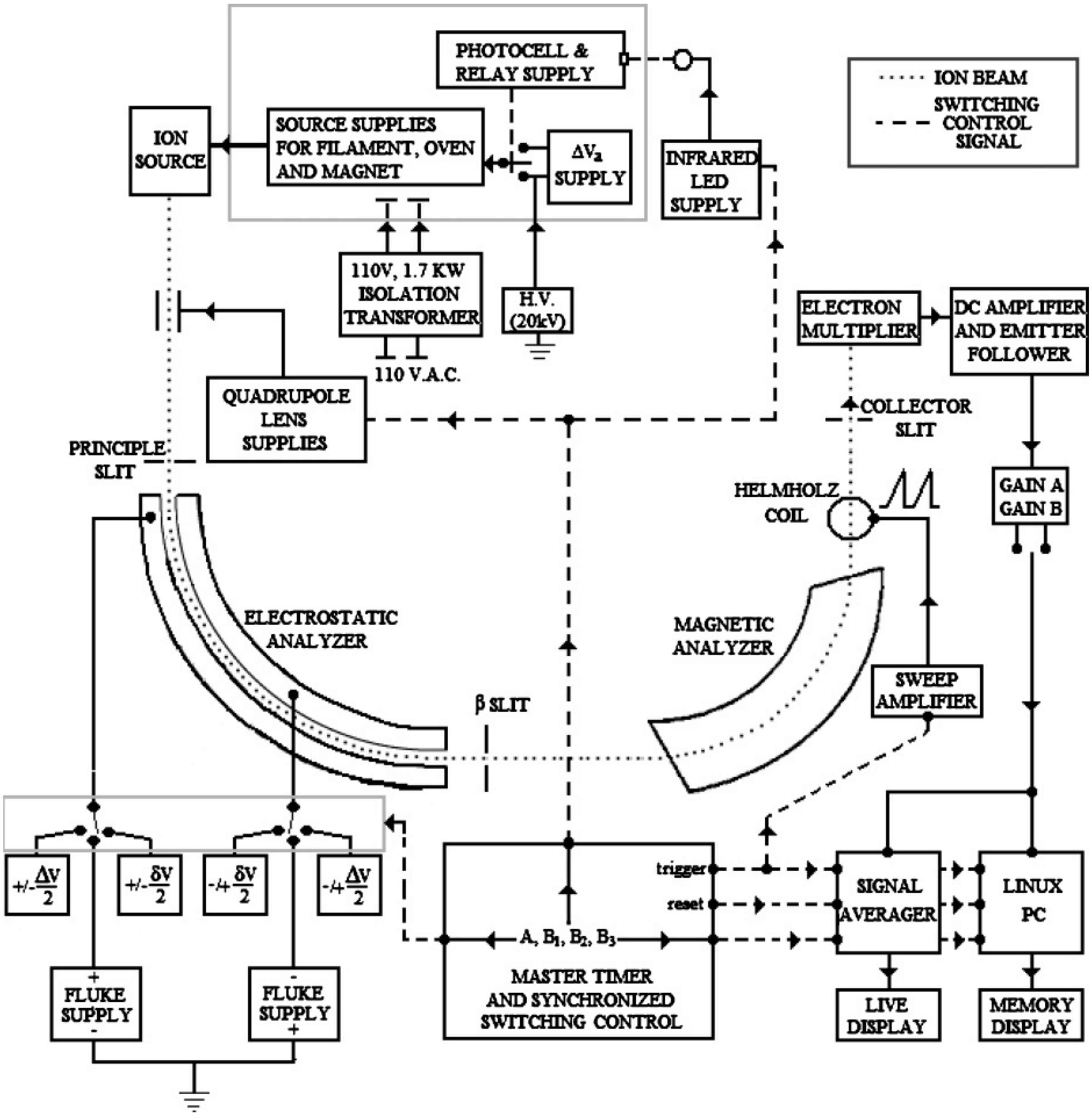

FIG. 1. Schematic diagram of the University of Manitoba's double-focusing mass spectrometer showing the control and data acquisition systems.

and

$$\Delta M + M' = M, \tag{3}$$

and then

$$\Delta M = M'(\Delta V/V). \tag{4}$$

In this instrument, the peak position is very sensitive to the voltage applied to the electrostatic analyzer and relatively insensitive to other potentials, such as the source potential. Accordingly, the position of the peak M' is matched to the position of peak M and the potential ΔV that corresponds to this match is measured relative to V, which is then used to calculate the mass difference.

To satisfy rigorously the conditions required by the Swann-Bleakney theorem, the source potential is also switched by the corresponding amount, ΔV_a, as are those applied to the quadrupole lens that precedes the principal slit (see Fig. 1).

In the case of ions that are chemically dissimilar, it has been shown that the two members of such a doublet may be formed in different locations in the ion source and experience somewhat different accelerating potentials. This may be tested by setting the conditions for a match and then slowly increasing the source potential, V_a. If the two members of the doublet acquire the correct energy, they will disappear simultaneously; that is, they travel along the same path and hit the outer edge of the β-slit in Fig. 1 for the same value of the source voltage,

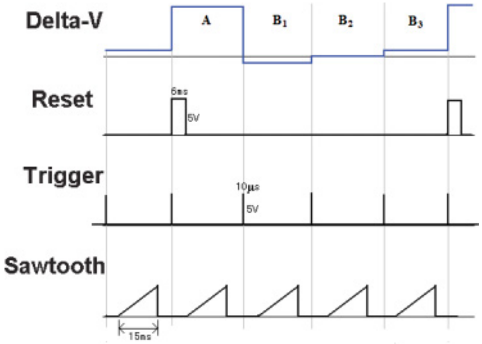

FIG. 2. (Color online) Master timing signals of the mass spectrometer.

V_a. If this test shows that the two members of the doublet are not following the same path, ΔV_a is adjusted so that they do.

C. Operation of the mass spectrometer

Details of the procedure for focusing the mass spectrometer have been given previously [4,11].

Peak matching can be performed visually. If all of the voltages are switched on alternating sweeps, ΔV is adjusted until the peaks for M and M' coincide on the live display oscilloscope. The peak heights are adjusted by the gains A and B, and alternate sweeps are displaced so that both peaks are clearly seen. The values of ΔV relative to V are measured precisely by a custom potentiometer (not shown in Fig. 1) and voltage divider described in detail by Bishop and Barber [12] and, in the current configuration, by Barillari *et al.* [8].

The measurements reported in this work were made by a computer-assisted method that follows the general concept of the visual technique. On the first sweep (labeled A in Fig. 2), the ΔV is added to V, along with all of the other required switched voltages, and the peak for M' is detected. On the second sweep, labeled B_1, the very small voltage $-\delta V$ is added to V. On the third sweep, labeled B_2, nothing is added to V and the reference position of mass M is detected. On the fourth sweep, labeled B_3, $+\delta V$ is added to V. The effect of adding $\pm\delta V$ to V in the second and fourth sweeps is to displace the peak for M on either side of its reference position in sweep 3 by something like 1/10th of a peak width.

The required control signals are provided by the master timing unit shown in Fig. 2. The details of the isolated switching circuits that actually provide ΔV and $\pm\delta V$, as well as a description of the precision potentiometer with which these voltages are measured, have been given by Barillari *et al.* [8]. As indicated in Fig. 2, the timing for the sawtooth is slightly offset from that of the trigger pulse in order to allow for a settling time for the switched potentials.

In the computer-matching technique, the peak positions for the recorded spectra for sweeps 2, 3, and 4 are compared with the position of the peak for sweep 1. With the related measured values for ΔV and $\pm\delta V$, the value that corresponds to the matched condition is calculated.

Computer matching has the advantage that it reduces sensitivity to small variations in peak intensity and provides improved precision with later off-line analysis.

Some of the signal averaging and pulse-count recording apparatus are new with this work. In detail, the pulse-count data from the channeltron are accumulated in multiple channels in a Cypress CY7C64613–128NC second-generation, full-speed Universal Serial Bus (USB) microcontroller chip. The data are buffered into a sweep packet, then transferred via USB to be recorded in a dedicated personal computer (PC). Each sweep packet contains the data from the four sweeps, which are subsequently displayed in real time on the computer and stored in memory. The data stored in the dedicated PC can be exported later as a complete data set for the matching analysis.

To reduce the likelihood of having systematic errors in a given match, it has been our established practice to use eight different configurations for a match in the course of determining the value for one run. Thus, the direction of the sawtooth sweep, the choice of adding or subtracting ΔV, and the sequence of adding the $\pm\delta V$ provide eight permutations of the matching parameters. It should be noted that no evidence for systematic errors associated with these permutations has been observed in this or previous work. The weighted mean of the values for the eight configurations is taken as the value for that run. The values for several runs provide the final result for that measurement.

In early work with this mass spectrometer, Southon *et al.* [13] established that there could be surface charges accumulated on the ESA plates. This means that the electric field, E, seen by the ion beam is not rigorously related to the applied potential, V, which is actually measured. To correct for this, a wide calibration doublet (where ΔM is usually ~1 u) is used to determine the correction required. Most corrections are of the order of a few hundred parts per million, as was the case in the present work.

III. RESULTS AND DISCUSSION

Inasmuch as the signal-averaging apparatus had been modified from that of previous work, three well-known doublets, given as A, B, and C in Table I, were determined to confirm that no unexpected systematic error had been introduced with this

TABLE I. New measurements (μu).

Code	Mass difference	This work	Comparison	Difference	Reference
A	^{116}Cd^{35}Cl$-^{114}$Cd^{37}Cl	4347.46 ± 0.44	4348.7 ± 1.2	-1.2 ± 1.3	Meredith *et al.* [14]
			4347.4 ± 2.2	$+0.1 \pm 2.2$	Audi *et al.* [15]
B	^{137}Ba^{35}Cl$-^{135}$Ba^{37}Cl	3089.1 ± 0.6	3088.9 ± 0.1	0.2 ± 0.6	Audi *et al.* [15]
C	^{138}Ba^{35}Cl$-^{136}$Ba^{37}Cl	3621.1 ± 0.6	3621.4 ± 0.1	-0.3 ± 0.6	Audi *et al.* [15]
D	^{136}Xe$-^{136}$Ba	2639.6 ± 0.6	See Table II		

TABLE II. Double-β decay energy for ^{136}Xe (keV).

Mass difference	This work	Comparison	Difference	Reference
^{136}Xe$-^{136}$Ba	$2458.73 \pm .56$	2462 ± 7	-3 ± 7	Audi *et al.* [15]
		2479 ± 79	-20 ± 79	Avignone *et al.* [17]
		2462.7 ± 4.3	-4.0 ± 4.3	ISOLTRAP [18]
		2457.83 ± 0.37	-0.9 ± 0.7	FSU Penning trap [19]

device. The Cd doublet is one we had studied in previous work [14]. The Ba doublets were conveniently available because the sample material for the doublet of primary interest was $BaCl_2$.

The new values for these doublets are given in Table I. For doublet A, a comparison value from work done previously with this instrument [14] is given, as well as the "best" value derived in a least-squares evaluation of all atomic masses and mass differences from the 2003 atomic mass evaluation (AME2003) of Audi *et al* [15]. Similarly, comparison values from the AME2003 are given for the Ba doublets. The AME2003 values reflect the very high precision associated with (n, γ) input Q values [16] that are available for these isotopes of Ba. It is evident that the agreement is excellent for all three doublets.

The new value for the ^{136}Xe$-^{136}$Ba mass difference is also given in Table I (in μu) and is the result of five runs. In Table II, this mass difference, expressed in kilo-electron-volts, is compared with values from other work. Here the conversion factor 931.494 013(37) MeV/u has been used [16]. The value measured in this work agrees very well with the rather large uncertainty of the Audi *et al.* AME2003 value [15] and easily falls within the very large uncertainty of the Monte Carlo result [17].

The last two values in Table II come from Penning trap measurements of the absolute mass for ^{136}Xe, where each is then combined with the value for the mass of ^{136}Ba from the AME2003 [15] to obtain the mass difference shown.

In the AME2003, the Ba masses are linked by many measured mass differences to distant nuclides (viz. W) located higher in the atomic mass table and for which precise absolute masses have been determined. While there are also absolute masses determined for nuclides lying lower and nearer in the atomic mass table (viz. Xe), the mass difference links between Ba and these lighter nuclides are not strong. In principle then, the value of the absolute mass of ^{136}Ba in the AME2003 (least-squares evaluation) could drift systematically in the calculation.

In contrast with the Penning trap measurements, the value in this work is a *direct* determination of the ^{136}Ba$-^{136}$Xe atomic mass difference. That the agreement with the Penning trap measurements is so good indicates that the atomic masses of the AME2003 have apparently not accumulated a significant systematic bias in the Ba region. Conversely, the addition of the value of the mass difference from this work will improve the reliability and precision of masses and mass differences in this immediate region, as derived in a new least-squares evaluation of the data. Finally, this new value gives a precise value for the energy that is shared by the two β particles in the neutrinoless double-β decay of ^{136}Xe and defines a very narrow energy window within which such a rare event might be sought.

ACKNOWLEDGEMENT

This work was supported by a research grant from the Natural Sciences and Engineering Research Council of Canada.

[1] M. Goeppert-Mayer, Phys. Rev. **48**, 512 (1935).
[2] W. H. Furry, Phys. Rev. **56**, 1184 (1939).
[3] J. G. Hykawy, J. N. Nxumalo, P. P. Unger, C. A. Lander, R. D. Peters, R. C. Barber, K. S. Sharma, and H. E. Duckworth, Nucl. Instrum. Methods Phys. Res. A **329**, 423 (1993).
[4] R. C. Barber, R. L. Bishop, H. E. Duckworth, J. O. Meredith, F. C. G. Southon, P. Van Rookhuyzen, and P. Williams, Rev. Sci. Instrum. **42**, 1 (1971).
[5] H. E. Duckworth, R. C. Barber, and V. S. Venkatasubramanian, *Mass Spectroscopy*, 2nd ed. (Cambridge University Press, Cambridge, UK, 1986), p. 101.
[6] D. K. Barillari, J. V. Vaz, R. C. Barber, and K. S. Sharma, Phys. Rev. C **67**, 064316 (2003).
[7] H. Hintenberger, and L. A. König, *Advance in Mass Spectroscopy*, edited by J. D. Waldron (Pergamon Press, London, 1959), p. 16.
[8] D. K. Barillari, J. V. Vaz, R. C. Barber, and K. S. Sharma, Phys. Rev. C **67**, 064316 (2003).
[9] W. F. G. Swann, J. Franklin Inst. **212**, 439 (1931).
[10] W. Bleakney, American Physics Teacher **4**, 12 (1936).
[11] R. C. Barber, Can. J. Phys. **43**, 716 (1965).
[12] R. L. Bishop, and R. C. Barber, Rev. Sci. Instrum. **41**, 327 (1970).
[13] F. C. G. Southon, J. O. Meredith, R. C. Barber, and H. E. Duckworth, Can. J. Phys. **55**, 383 (1977).
[14] J. O. Meredith, F. C. G. Southon, R. C. Barber, P. Williams, and H. E. Duckworth, Int. J. Mass Spectrom. Ion Phys. **10**, 359 (1973).
[15] G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. A **729**, 337 (2003).
[16] G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. A **729**, 129 (2003).
[17] F. T. Avignone, G. S. King, and Y. G. Zdesenko, New J. Phys. **7**, 6 (2005).
[18] A. Herlet *et al.*, Int. J. Mass Spectrom. **251**, 131 (2006).
[19] M. Redshaw, E. Wingfield, J. McDaniel, and E. G. Myers, Phys. Rev. Lett. **98**, 053003 (2007).