Isotope Shift Measurements of Muonic X-Rays in $^{134,136,138}\text{Ba}$

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The isotope shifts of muonic X-rays for the three stable Ba-isotopes $^{134,136,138}\text{Ba}$ have been measured with high accuracy. Especially the differences in the rms radii $\Delta\langle r^2 \rangle$ have been determined in a model independent way and have been used to calibrate optical isotope shift data.

I. Introduction

High precision studies of muonic X-rays are well suited to extract information about nuclear sizes and shapes from the measured transition energies. For the monopole charge radii recent work has led to a method of analysis which, in a nearly model independent way can extract different generalized moments for the nuclear charge density [1].

Even with the present beam intensities available at the meson factories the minimal amount of target material necessary to produce statistically significant spectra is still of the order of $\gtrsim 100\text{ mg}$.

In contrast high resolution laser spectroscopic studies can only determine frequency shifts which are a function of one moment of the charge distribution, essentially the root mean square radius. Typical for this method is not only the high relative accuracy but also the ability to work with minute amounts of material. In the case of the Ba-isotopes the isotope chain investigated ranges from $A=122$ to $A=146$ [2, 3].

It was the purpose of the present investigation to determine the muonic transition energies and hence the generalized Barrett moments of the charge distribution of the Ba-isotopes with an accuracy as high as possible for a whole series of transition energies. Such a procedure allows to perform internal consistency checks, which are important to test the va-

lidity of a number of necessary corrections to the measured X-ray energies.

Moreover, from a series of generalized moments the root mean square radius not measured directly with muonic atoms can be extracted in a model independent way and a calibration of the optical data can be performed with high accuracy.

II. The Experiment

The measurement itself was performed at the high intensity muon channel $\mu E1$ at the Schweizerisches Institut für Nuklearforschung (SIN). The targets and their isotopic composition are listed in Table 1.

At first a survey measurement was performed. It served to determine the ability not only to measure the main transitions $2p-1s$ and $3d-2p$ but also to check the possibility to measure the weak, but important $2s-2p$ transitions with a good peak to background ratio which turned out to be feasible. For the main experiment two pairs of targets were built: $^{134,138}\text{Ba}$ and $^{136,138}\text{Ba}$. The targets of each pair were as identical as possible.

In each measurement the X-rays were registered with up to three semiconductor detectors in a conventional way. The parameters of the detector sys-

Table 1. Isotope compositions of the targets used

Material	Amount(g)	Isotope abundance (%)				
		138	137	136	135	134
^{138}Ba	57.0	98.04 (10)	—	<2.0	—	<2.0
^{136}Ba	22.6	4.56 (5)	1.82 (5)	92.65 (10)	0.88 (5)	0.09 (3)
^{134}Ba	4.5	6.92 (5)	1.55 (2)	1.72 (2)	3.54 (2)	86.22 (10)

Table 2. Parameters of the semiconductors used

Type	Volume	Efficiency (1,332 keV)	Resolution
Ge(Li) coaxial	100 cm ³	20 %	2.1 keV at 1,322 keV
Ge HP n-type	26 cm ³	13 %	1.9 keV at 1,322 keV
Ge intrinsic planar	0.56 cm ³	—	1.1 keV at 430 keV

tems used are listed in Table 2. Two sets of measurements have been performed. In each measurement the two targets were interchanged automatically every 30–40 s, i.e. after a preset number of muon stops in a target had been registered. In this way any relative energy shift in the spectrometer system could be minimized and two spectra could be investigated under the same background conditions. The good performance of the method is visualized in Fig. 1 and Fig. 2. There, difference spectra have been

Fig. 1. Single and difference spectra of the 2–1 energy region of ^{138}Ba and ^{134}Ba with full energy peak (F.P.), Single (S.E.) and Double Escape peak (D.E.).

Fig. 2. Single and difference spectra of the 3–2 energy region of ^{138}Ba and ^{134}Ba

Table 3. Radioactive sources to calibrate the spectra (energy in keV)

^{24}Na	1,368.643 (20) 1,732.028 (100) 2,243.031 (100) 2,754.034 (38)	^{60}Co	1,173.238 (15) 1,332.513 (18)	^{207}Bi	569.653 (20) 1,063.630 (30) 1,770.220 (40)
^{110}Ag	446.812 (4) 620.358 (3) 657.761 (2) 677.627 (4) 687.010 (4) 706.680 (5) 744.279 (5) 763.949 (5) 818.032 (5) 884.684 (5) 937.491 (5) 1,384.300 (4) 1,475.786 (5) 1,505.036 (5) 1,562.301 (6)	^{56}Co	846.772 (13) 1,037.840 (15) 1,175.102 (16) 1,238.282 (17) 1,360.250 (70) 1,771.351 (26) 2,015.181 (28) 2,034.755 (29) 2,598.458 (33) 3,201.962 (46) 3,253.416 (45) 3,272.990 (45) 3,451.152 (47) 3,547.925 (61)	^{133}Ba	53.156 (5) 79.623 (5) 80.999 (4) 160.609 (25) 223.116 (35) 276.398 (2) 302.853 (1) 356.017 (2) 383.851 (3)

produced showing the isotope shift directly in the dispersive-like structure of the resulting spectra. Moreover the assumption of equal background is validated by the fact that the background of the difference spectra is comparable to zero. Any nuclear gamma line normally different in intensity for two isotopes would show up as a deviation from this behaviour.

In order to study the influence of different count rate conditions on the peak positions a relatively high number of spectra (=42) have been taken with different radioactive calibration sources (Table 3) in front of the different detectors and under different shielding conditions.

III. The Evaluation Procedure

The process of evaluation of the data proceeded in two different steps. Initially the energies of the muonic transitions have been extracted in a least squares fitting procedure in the usual way. The nonlinearity of the ADC was determined from the positions of the radioactive sources and from known energies of muonic lines and served to determine the absolute values of the muonic energies for ^{138}Ba for the different sets of measurement. The absolute and relative positions of the muonic ^{136}Ba and ^{134}Ba lines, respectively, were then determined, taking into account the relative amount of the other isotopes. A set of muonic energies was then established (Table 4). Special care was taken in the evaluation of the $2p$

– $1s$ transitions. Here not only the full energy peak but also the single and especially the double escape peak with a known energy distance from the full energy peak were evaluated in order to check for possible nonlinearities and shifts. Additionally to the calibration lines from sources the double escape line of the muonic $2p_{3/2} - 1s_{1/2}$ transition of ^{206}Pb was used. The energy of this transition was taken to be 5,972.80(41) keV [4] and served as calibration line above 3.9 MeV. During the whole fitting procedure already evaluated transition energies of the isotope examined as well as those from the other Ba-isotopes were again used for calibration.

In the second step the generalized Barrett moments and the root mean square radii for the different isotopes were determined. In order to do that several corrections had to be applied before comparing the measured energies with the program MUON [5]

Table 4. Measured energies of the three Ba-isotopes in keV

Transition	^{138}Ba	^{136}Ba	^{134}Ba
$2p_{3/2} - 1s_{1/2}$	3,987.998 (20)	3,991.105 (25)	3,992.688 (32)
$2p_{1/2} - 1s_{1/2}$	3,922.194 (23)	3,925.224 (32)	3,926.774 (39)
$3d_{5/2} - 2p_{3/2}$	1,227.015 (11)	1,227.205 (20)	1,227.418 (21)
$3d_{3/2} - 2p_{1/2}$	1,283.399 (18)	1,283.643 (29)	1,283.896 (29)
$3d_{3/2} - 2p_{3/2}$	1,217.652 (39)	1,217.857 (45)	1,218.115 (88)
$2s_{1/2} - 2p_{1/2}$	405.271 (46)	404.841 (46)	404.792 (88)
$2s_{1/2} - 2p_{3/2}$	339.497 (38)	339.106 (42)	338.871 (75)
$4f_{7/2} - 3d_{5/2}$	433.914 (9)	433.908 (9)	433.904 (10)
$4f_{5/2} - 3d_{3/2}$	441.370 (9)	441.369 (9)	441.369 (10)

Table 5. Corrections to muon binding energies (keV) for ^{138}Ba

State	Vacuum polarization			Muon	Lamb shift		Rel. recoil corr.	Electron screening
	$\alpha(Z\alpha)$	$\alpha^2(Z\alpha)$	$\alpha(Z\alpha)^{n \geq 3}$		$\alpha(Z\alpha)$	$\alpha^2(Z\alpha)$		
$1s_{1/2}$	41.998	0.346	-0.173	0.149	-2.018	-0.099	0.244	0.001
$2s_{1/2}$	9.660	0.075	-0.052	0.023	-0.384	-0.016	0.041	0.006
$2p_{1/2}$	13.865	0.105	-0.074	0.009	-0.044	-0.019	0.033	0.003
$2p_{3/2}$	12.829	0.097	-0.070	0.006	-0.158	-0.016	0.029	0.003
$3d_{3/2}$	3.692	0.026	-0.028	—	-0.012	-0.001	0.004	0.011
$3d_{5/2}$	3.567	0.025	-0.027	—	-0.009	-0.001	0.004	0.011
$4f_{5/2}$	1.251	0.008	-0.013	—	-0.003	—	0.001	0.029
$4f_{7/2}$	1.232	0.009	-0.012	—	-0.002	—	0.001	0.029

which delivers energies for a finite size nucleus in the ground state without nuclear polarization corrections. For the muonic states of the ^{138}Ba -isotope the corrections calculated from MUON are listed as an example in Table 5.

The most important correction for an isotope shift measurement is the correction for the nuclear polarization shift resulting from the low lying nuclear states which are different for the different isotopes used due to the increasing deformation with decreasing neutron number.

The energies of the nuclear states considered in the model space and the $B(E2)$ values and quadrupole moments used were taken from references [6, 7]. The model space consisted of the 0^+ , 2^+ , 2^{+} , 4^+ nuclear states and the muonic $1s$, $2s$, $2p$, $3p$ and $3d$ states. The calculations were performed on the VAX-computer at SIN using the RUPP program originally written by Rinker [5] and implemented at SIN by the Fribourg group [8]. This program was

checked against an earlier publication of the LAMPF group [9]. Their results are well reproduced.

For the nuclear polarization shifts for the high lying nuclear states, however, we found a discrepancy of about 200 eV between our calculation and the values used by the LAMPF group [10, 11]. This difference will only slightly influence the resulting $\langle r^2 \rangle$ and not at all the $\Delta\langle r^2 \rangle$ values which will be used for the comparison with the optical isotope shift data.

The calculated shifts due to the nuclear polarization of low lying nuclear states agree with the values of the LAMPF group for the $1s$, $2s$, and $3d$ states. The corrections we used for the $2p$ states could be checked experimentally as is discussed below. The resulting corrections for the $2p$ levels were about 400 eV (^{138}Ba), 600 eV (^{136}Ba) and 930 eV (^{134}Ba). Their accuracy was checked to be about 30 eV in the most affected case of ^{134}Ba .

With the such corrected energies, model independent

Table 6a. Corrected energies and evaluated k and R_k values for the ^{138}Ba

Transition	Energy (keV)	k	R_k (fm)	C_z (mf/keV)
$2p_{3/2} - 1s_{1/2}$	3,986.184 (21)	2.19359 (4)	6.18976 (5)	— 2.60
$2p_{1/2} - 1s_{1/2}$	3,920.422 (23)	2.18635 (2)	6.18902 (6)	— 2.59
$3d_{5/2} - 2p_{3/2}$	1,226.668 (12)	4.05712 (5)	6.32024 (91)	— 82.7
$3d_{3/2} - 2p_{3/2}$	1,217.305 (39)	4.05398 (21)	6.3156 (32)	— 81.5
$3d_{3/2} - 2p_{1/2}$	1,283.010 (19)	3.49299 (12)	6.28499 (92)	— 51.3
$2s_{1/2} - 2p_{3/2}$	339.459 (39)	1.61810 (3)	6.14348 (71)	+ 18.7
$2s_{1/2} - 2p_{1/2}$	405.191 (46)	1.48828 (9)	6.12913 (99)	+ 21.7
$3d_{5/2} - 1s_{1/2}$	5,212.826 (23)	2.25000 (6)	6.19411 (6)	— 2.72
$3d_{3/2} - 1s_{1/2}$	5,203.406 (29)	2.25000 (6)	6.19404 (7)	— 2.33
$2s_{1/2} - 1s_{1/2}$	4,325.617 (33)	2.29542 (7)	6.19744 (11)	— 3.25
$2p_{3/2} - 2p_{1/2}$	65.807 (17)	2.57935 (13)	6.2205 (23)	— 133.1
$4f_{7/2} - 3d_{5/2}$	433.914 (9)	6.374 (13)	6.67 (18)	-20,045.0
$4f_{5/2} - 3d_{3/2}$	441.370 (9)	5.343 (16)	6.462 (96)	-10,687.0

Table 6b. Corrected energies and evaluated k and R_k values for the ^{136}Ba

Transition	Energy (keV)	k	R_k (fm)	C_Z (mfm/keV)
$2p_{3/2} - 1s_{1/2}$	3,989.274 (27)	2.19359 (1)	6.18164 (6)	— 2.57
$2p_{1/2} - 1s_{1/2}$	3,923.360 (33)	2.18469 (2)	6.18110 (9)	— 2.83
$3d_{5/2} - 2p_{3/2}$	1,226.634 (23)	4.05708 (5)	6.3219 (16)	— 80.9
$3d_{3/2} - 2p_{3/2}$	1,217.287 (46)	4.05482 (12)	6.3160 (37)	— 83.0
$3d_{3/2} - 2p_{1/2}$	1,283.039 (31)	3.49091 (20)	6.2827 (15)	— 51.0
$2s_{1/2} - 2p_{3/2}$	338.879 (43)	1.61924 (4)	6.13282 (80)	+ 18.7
$2s_{1/2} - 2p_{1/2}$	404.580 (47)	1.48854 (14)	6.11601 (98)	+ 21.4
$3d_{5/2} - 1s_{1/2}$	5,215.908 (32)	2.24780 (1)	6.18603 (8)	— 2.50
$3d_{3/2} - 1s_{1/2}$	5,206.399 (43)	2.24790 (1)	6.18621 (11)	— 2.50
$2s_{1/2} - 1s_{1/2}$	4,328.047 (37)	2.29534 (7)	6.18988 (11)	— 2.85
$2p_{3/2} - 2p_{1/2}$	65.868 (24)	2.57935 (29)	6.2124 (32)	— 134.5
$4f_{7/2} - 3d_{5/2}$	433.908 (9)	6.373 (21)	6.69 (21)	—22,814.0
$4f_{5/2} - 3d_{3/2}$	441.369 (9)	5.337 (16)	6.415 (99)	—10,953.0

Table 6c. Corrected energies and evaluated k and R_k values for the ^{134}Ba

Transition	Energy (keV)	k	R_k (fm)	C_Z (mfm/keV)
$2p_{3/2} - 1s_{1/2}$	3,990.846 (38)	2.19352 (1)	6.17751 (8)	— 2.60
$2p_{1/2} - 1s_{1/2}$	3,924.934 (44)	2.18460 (9)	6.17690 (11)	— 2.82
$3d_{5/2} - 2p_{3/2}$	1,226.233 (29)	4.05702 (5)	6.3315 (17)	— 82.5
$3d_{3/2} - 2p_{3/2}$	1,217.192 (30)	4.05489 (18)	6.3218 (72)	— 81.2
$3d_{3/2} - 2p_{1/2}$	1,282.971 (35)	3.49312 (27)	6.2852 (15)	— 51.6
$2s_{1/2} - 2p_{3/2}$	338.331 (76)	1.62038 (13)	6.1228 (14)	+ 18.5
$2s_{1/2} - 2p_{1/2}$	404.250 (90)	1.49000 (10)	6.1091 (19)	+ 21.7
$3d_{5/2} - 1s_{1/2}$	5,217.406 (31)	2.24600 (9)	6.18189 (9)	— 2.39
$3d_{3/2} - 1s_{1/2}$	5,207.945 (48)	2.24790 (1)	6.18225 (12)	— 2.50
$2s_{1/2} - 1s_{1/2}$	4,329.218 (62)	2.29340 (1)	6.18605 (19)	— 3.00
$2p_{3/2} - 2p_{1/2}$	65.926 (28)	2.57935 (27)	6.2047 (37)	— 133.0
$4f_{7/2} - 3d_{5/2}$	433.904 (10)	6.376 (24)	6.66 (23)	—23,302.0
$4f_{5/2} - 3d_{3/2}$	441.369 (10)	5.329 (16)	6.35 (12)	—11,955.0

Barrett moments and equivalent radii have been derived from the data. As usual the fact was used that each transition determines a certain moment $\langle r^k e^{-\alpha r} \rangle$ of the charge distribution. The parameter α can be assumed to be the same for all transitions and isotopes used with the value $\alpha = 0.1161$. The parameter k and the equivalent radius R_k for a homogeneously charged sphere with the same moment have been determined separately for each transition. The values are listed in Table 6 also including energy differences not measured directly as transition energies but derived from sum rules ($2p_{3/2} - 2p_{1/2}$, $3d - 1s$, $2s - 1s$).

These values represent the total knowledge about the nuclear charge distribution which can be extracted from muonic atom experiments. Moreover plotting R_k against k the graphs can be checked for inconsistencies which could reveal systematic errors in both the measurement and in the corrections. Especially the $2p - 1s$ transitions determining R_k val-

ues with $k \simeq 2.19$ could be tested for the corrections applied because the $3d - 1s$ and $2s - 1s$ energies determine R_k values directly in the neighbourhood without being influenced by $2p$ shifts. In Fig. 3 R_k is plotted against k for a narrow range of k where the curve can be assumed to be linear. The position of the R_k values for the $2 - 1$ transitions strongly supports our assumption about the validity of the $B(E2)$ correction for low lying nuclear states.

In order to compare the measured R_k values with the mean square radius from optical data one usually leaves the degree of model independence guaranteed by the analysis of Barrett moments. In our case, however, the degree of model independence is preserved with the following procedure:

We write

$$\begin{aligned}
 \langle r^2 \rangle &= \langle r^2 e^{-\alpha r} e^{+\alpha r} \rangle \\
 &= \langle r^2 e^{-\alpha r} \rangle + \alpha \langle r^3 e^{-\alpha r} \rangle + (\alpha^2/2) \langle r^4 e^{-\alpha r} \rangle \\
 &\quad + (\alpha^3/6) \langle r^5 e^{-\alpha r} \rangle + \dots
 \end{aligned}$$

Fig. 3. Equivalent radii R_k against k for $2p-1s$, $3d-1s$ and $2s-1s$ transitions

and use the fact that this series converges rapidly. Using the equivalent radii description the terms of the expansion are slightly more complicated

$$\begin{aligned}
 \langle r^2 \rangle &= X_{R_2} & k=2 \\
 &+ 5X_{R_3} - 3R_3^2 e^{-\alpha R_3} & k=3 \\
 &+ 15X_{R_4} - (9 + 1.5\alpha R_4)R_4^2 e^{-\alpha R_4} & k=4 \\
 &+ 35X_{R_5} - (21 + 3.5\alpha R_5 + 0.5\alpha^2 R_5^2) & \\
 &\cdot R_5^2 e^{-\alpha R_5} + \dots & k=5
 \end{aligned}$$

where $X_{R_k} = (3/R_k^3) \int_0^{R_k} r^k e^{-\alpha r} dr$.

Clearly any other moment $\langle r^l \rangle$, $1 \leq l \leq 5$ could be determined in a corresponding way.

The determination of $\langle r^2 \rangle$ and $\Delta \langle r^2 \rangle$ is straightforward now. The R_k , k curve of ^{138}Ba was fitted with a parabolic curve and the R_k ($k=2, 3, 4, 5, 6, 7$)-values were read off. From a linear fit to the R_k-k curves of the different isotope pairs the ΔR_k ($k=2, 3, 4, 5, 6, 7$)-values were obtained and used to con-

Table 7. The different terms of the series of $\langle r^2 \rangle$ for the three Ba-isotopes

k	^{138}Ba	^{136}Ba	^{134}Ba
2	12.65612 (50)	12.62988 (56)	12.61451 (64)
3	7.63846 (13)	7.6270 (15)	7.6281 (17)
4	2.43581 (120)	2.43715 (153)	2.44521 (170)
5	0.541510 (70)	0.543831 (74)	0.54340 (119)
6	0.093574 (40)	0.094464 (40)	0.096621 (6)
7	0.013925 (50)	0.01341 (6)	0.01411 (7)
Rest	0.00174	0.00174	0.00174
$\langle r^2 \rangle$ (fm ²)	23.3811 (20)	23.3478 (22)	23.3433 (28)
$\langle r^2 \rangle^{1/2}$ (fm)	4.8354 (10)	4.8320 (11)	4.8315 (14)
Δr^2 (fm ²)			
compared to ^{138}Ba		0.0333 (22)	0.0379 (28)

struct the corresponding R_k values for the ^{134}Ba and ^{136}Ba -isotopes. Such a procedure also allows a transparent evaluation of the error in the final results.

Whereas the error of the R_k ($k=2, 3, 4, 5, 6, 7$)-values for the ^{138}Ba -isotope had to be extracted from the parabolic fitting routine, the error for the isotope pairs are even simpler to obtain from the linear fit of the ΔR_k-k curves. The final error for the rms-radii is then established by error progression from the different terms in the sum for $\langle r^2 \rangle$. These terms are listed in Table 7 for all three isotopes together with the final values for $\langle r^2 \rangle$ and $\Delta \langle r^2 \rangle$. The errors given are smaller than these in the recent publication of the LAMPF group [10] and the values of $\Delta \langle r^2 \rangle$ for the isotope pairs disagree with their measurement on the level of 2 to 3 standard deviations.

IV. King-Plot Parameters

The $\Delta \langle r^2 \rangle$ values of muonic atoms can be compared with the frequency shifts of optical measurements. The frequency shifts related to the transitions in ^{138}Ba can be written as

$$\Delta \nu = \Delta \nu_{\text{mass}} + \Delta \nu_{\text{field}}$$

or

$$\Delta \nu_{AA'} = M \{ (A - A') / AA' \} + F \Delta \langle r^2 \rangle_{AA'}$$

M is the so called mass effect factor and is a sum of the normal and the specific mass factor effect reflecting the influence of electron correlation effects upon the reduced mass corrections. F is the so called electronic factor which is proportional to the overlap of the electronic wavefunction with the nucleus.

Combining our values of $\Delta\langle r^2 \rangle$ with those of the Karlsruhe group [2] and the Mainz group [3] in a regression analysis M and F could be determined to be $M = -4.1 (14.0) \text{ MHz}$ and $F = -3,990 (652) \text{ MHz/fm}^2$.

V. Conclusion

It could be shown that with highly accurate measurements of muonic atom X-rays using as many different transitions as possible, internal consistency checks can serve to test the reliability of necessary corrections to be made.

Moreover, from the differences of many "Barrett" equivalent radii Barrett moment differences in root mean square radii could be obtained in a model independent way.

Therefore a direct calibration of optical isotope shifts could be achieved which in turn leads to a decrease of error bars for these isotope shift measurements. The determined mass shifts and electronic factors themselves provide a means to test the validity of the highly developed many body calculation techniques in atomic physics.

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References

1. Barrett, R.C.: Phys. Lett. B **33**, 388 (1970)
2. Bekk, K., Andl, A., Goring, S., Hanser, A., Nowicki, G., Rebel, H., Schatz, G.: Z. Phys. A - Atoms and Nuclei **291**, 219 (1979)
3. Mueller, A.C., Buchinger, F., Klempt, W., Otten, E.W., Neugart, R., Ekstroem, C., Heinemeier, J., ISOLDE Collaboration: CERN report EP-82-162
4. Kessler, D., Mes, H., Thompson, A.C., Anderson, H.L., Dixit, M.S., Hargrove, C.K., McKee, R.J.: Phys. Rev. C **11**, 1719 (1975)
5. Rinker, G.A.: Comput. Phys. Commun. **16**, 221 (1979)
6. Christy, A., Häusser, O.: Nucl. Data Tables **11**, 281 (1972)
7. Kleinfeld, A.M., Bockisch, A., Lieb, K.P.: Nucl. Phys. A **283**, 526 (1977)
8. Ruetschi, A.: Private communication
9. Yamazaki, Y., Shera, E.B., Hoehn, M.V., Steffen, R.M.: Phys. Rev. C **18**, 1474 (1978)
10. Shera, E.B., Wohlfahrt, H.D., Hoehn, M.V., Tanaka, Y.: Phys. Lett. B **112**, 124 (1982)
11. Shera, E.B.: Private communication

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