BRIEF REPORTS

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Electron-γ angular correlations in ^{134}Ba

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Electron-γ directional correlation measurements have been done in ^{134}Ba for the first time using an apparatus including cooled Si surface barrier detector for the electrons and HPGe for the γ's. Experimental particle parameters for pure intense $E2$ transitions have been calculated from $\gamma\gamma$ and electron-γ results, giving $b_2(605K)=1.31(28)$ and $b_2(795K)=1.20(23)$. Some mixed transitions were also analyzed. The $326K$ electron conversion ratio $\alpha_{326K}=14(6)\times10^{-2}$ was measured. An upper bound for the $E0/E2$ mixing ratio was estimated to the $2^{+\prime}\rightarrow2^{+}$(563 keV) transition by the $e\gamma$ interference $E0/E2$ method, giving $q_K^2(E0/E2)\leqslant0.06$. [S0556-2813(98)00909-1]

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Conversion electrons have long helped to assert spin, parity and multipole mixing ratios [1–3]. The $2'^{+}\rightarrow2^{+}$ transition allows the electron mixing $E0$, $M1$ and $E2$ [4]. The $E0/E2$ mixing ratio can be inferred by electron-γ correlations or alternatively by the $\gamma\gamma$ indirect cascade method [5,6]. Although ^{134}Ba is not expected to have the $E0$ channel highly favored, we used our setup to investigate it and also to cross check data with the $\gamma\gamma$ experiment (see Fig. 1).

Our main goal was to measure directional $e\gamma$ angular correlations in ^{134}Cs decay for the first time. These data would provide particle parameters and a cross check of $\gamma\gamma$ results.

We describe the experimental methods, i.e., the sources preparation, electron-γ apparatus, and the method of acquiring and correcting data. We then discuss the electron-γ data are analyzed and compared to the predicted results using the theoretical particle parameters and multipole mixing ratios extracted from $\gamma\gamma$ measurements [7]. An upper limit for the $q_K(E0/E2)$ mixing ratio is inferred in the $2'^{+}\rightarrow2^{+}$ transition. The electron-γ data together with $\gamma\gamma$ data provided precise internal conversion coefficients (ICC) for the $795K$ and $802K$ cascades. A first evidence of the $326K$ transition is described and the ICC estimated. Finally the main results and conclusions are summarized.

A thin spot (<1 mg/cm^2, 3 mm diameter) of natural CsCl was made on a 99.99%, 0.7 mg/cm^2 aluminum foil, by vacuum deposition, for the $e\gamma$ experiment. The source was covered with a thin spot (~20 μg/cm^2, 5 mm diameter) of carbon to avoid deliquescence. The source was then irradiated at IPEN, Sao Paulo, with 10^{13} neutrons/cm^2 s flux for 200 h, resulting in a specific activity of about 10μCi. After fifteen days the aluminum contaminants (as Au) decayed.

The electrons were detected by a windowless Si surface barrier detector, surface area 200 mm^2, depletion depth 1.5 mm, reverse polarization tension 150 V, 2 μA leak current. A 17 keV resolution at room temperature was obtained with a ^{207}Bi thin calibration source. The Si detector was cooled down to -30 °C by means of a cold finger. Then the leak current dropped to 2 nA and the resolution improved to 6.5 keV. With the ^{134}Cs thin source the resolution was around 8.0 keV for the $605K$ conversion electrons. The Si detector was operated in vacuum and a device provided rotation maintaining vacuum better than 10^{-6} torr. The distance to the source was 3 cm. The solid angle was corrected assuming that the efficiency is constant with the absorption angle. The γ detector was a 50 cm^3 HPGe, 45.8 mm crystal diameter, 36.1 cm crystal length and placed 10.1 cm from the source. The solid angle corrections made in the $\gamma\gamma$ experiment were also done in the γ detector. The biparametric data were accumulated in two arrays of $4096(\gamma)\times2048(e)$ channels.

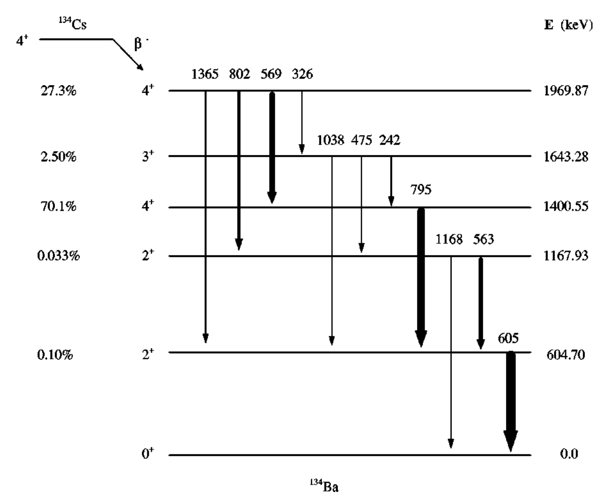

FIG. 1. Level scheme of ^{134}Ba from ^{134}Cs decay, β^- feeding taken from [19].

TABLE I. $e\gamma$ directional angular correlations in Ba^{134}. Our experimental data are presented in bold characters and below them are given the values predicted using experimental $\gamma\gamma$ multipole mixing ratios [7] and the theoretical particle parameters interpolated from [12]. The last column shows the superposing lines (SL) and background which significantly increased the errors. C=Compton.

No.	γ	Cascade (keV)	χ^2	α_0	A_{22}	A_{44}	SL
	475						
1		475γ $563K$	0.33	345(27)	**0.16(17)**	**−0.01(22)**	
					0.077	0.0027	
2		475γ $605K$	0.45	308(20)	**−0.11(13)**	**0.09(18)**	$563_{L,M}$
					0.115	0.0022	
3		475γ $1168K$	0.17	8.7(24)	**−0.48(53)**	**0.23(76)**	
					−0.460	−0.04	
	563						
4		$475K$ 563γ	0.34	293(25)	**−0.09(17)**	**0.21(25)**	$\mathrm{C}605_{\gamma}$
					0.029	0.007	
5		563γ $605K$	0.59	1715(35)	**−0.112(41)**	**−0.048(57)**	
				$\delta_\gamma=28.5$	−0.144	−0.026	
				$\delta_\gamma=10.9$	−0.199	−0.026	
6		$802K$ 563γ	0.52	776(15)	**−0.011(41)**	**−0.056(57)**	
					−0.010	0.00059	
	569						
7		569γ $605K$	0.08	3225(42)	**0.142(27)**	**0.001(38)**	
					0.161	0.0004	
8		569γ $795K$	0.16	1671(21)	**0.131(25)**	**−0.007(36)**	
					0.149	−0.026	
	605						
9		$475K$ 605γ	0.74	403(101)	**−0.15(50)**	**0.05(71)**	C,β^-
					0.08	0.02	
10		$563K$ 605γ	0.50	2266(100)	**−0.240(94)**	**0.13(14)**	$569_K,\beta^-$
					−0.147	−0.040	
11		$569K$ 605γ	2.1	4530(110)	**0.191(49)**	**0.022(69)**	$563_K,\beta^-$
					0.057	0.0006	
12		$795K$ 605γ	0.94	8619(80)	**0.143(20)**	**−0.015(27)**	802_K
					0.134	0.0020	
13		$802K$ 605γ	0.24	652(64)	**0.003(212)**	**0.14(29)**	795_K
					−0.028	0.001	
14		$1038K$ 605γ	0.10	37.6(67)	**0.39(37)**	**−0.11(51)**	
					0.150	0.084	
15		$1365K$ 605γ	0.51	31.4(37)	**0.39(25)**	**−0.41(32)**	
					0.119	0.26	
	795						
16		$569K$ 795γ	1.5	3768(90)	**0.042(49)**	**0.041(69)**	β^-
					0.057	−0.0004	
17		795γ $605K$	2.6	13016(102)	**0.115(17)**	**−0.071(24)**	$569_{L,M}$
					0.161	−0.00032	
	802						
18		802γ $563K$	0.87	1350(22)	**−0.017(34)**	**0.029(47)**	
					0.020	0.0003	
19		802γ $605K$	2.5	1115(11)	**0.024(40)**	**0.044(57)**	$563_{L,M}$
					−0.031	0.0003	
	1038						
20		802γ $1168K$	1.1	28(4)	**−0.07(27)**	**−0.22(37)**	
					0.122	−0.54	
21		1038γ $605K$	1.4	109(7)	**0.38(12)**	**0.13(17)**	
					0.352	0.0012	
	1168						
22		$475K$ 1168γ	0.76	51(6)	**−0.50(23)**	**0.34(34)**	
					−0.396	0.025	
23		$802K$ 1168γ	1.3	76(6)	**0.46(14)**	**0.09(20)**	
					0.134	0.002	
	1365						
24		1365γ $605K$	1.16	290(9)	**0.217(63)**	**−0.150(90)**	
					0.145	−0.0005	

Around 85 measurements of one hour each were made at 90°, 120°, 150°, 210°, 240°, 270°, and 167 one hour measurements at 180°. Half life effect was also corrected. A maximum of 3 keV shift and resolution $\leqslant 9$ keV in the 795 K line was accepted in the electron spectra.

A least-square fit to the correlation function, $W(\theta)$,

$$W(\theta)=\alpha_0[1+Q_{22}A_{22}P_2(\cos\,\theta)+Q_{44}A_{44}P_4(\cos\,\theta)] \tag{1}$$

was performed to the corrected coincidence rates to find α_0, $A_{22}=B_2(e)A_2(\gamma)$, and $A_{44}=B_4(e)A_4(\gamma)$ or alternatively $A_{22}=B_2(\gamma)A_2(e)$ and $A_{44}=B_4(\gamma)A_4(e)$ and thus 24 coincidence cascades were measured. The orientation coefficients B_λ and distribution coefficients A_λ are defined in Ref. [8] and depend on the multipole mixing ratio of the transition.

The γ detector geometrical correction factors Q_λ were computed using the method of Camp and van Lehn [9].

We assumed that the electron detector efficiency does not change with the entrance angle(θ_a) and its geometric correction must be $Q_2(e)=J_2/J_0=\nu(\nu+1)/2$ and $Q_4(e)=J_4/J_0=\nu(\nu+1)(7\nu^2-3)/8$, where $\nu=\cos\,\theta_a$ [9–11]. In our experiment $\theta_a=19.1°$ which gives $Q_2(e)=0.9189$ and $Q_4(e)=0.7468$.

The $e\gamma$ results for A_{22} and A_{44} obtained from experimental data using the fitting procedure are listed in bold in Table I. The values predicted using the experimental $\gamma\gamma$ multipole mixing ratios [7] and the theoretical particle parameters interpolated from Hager and Seltzer tables [12], are shown also below the data in bold characters. Although there are large errors in most cascades, there is an overall agreement between the results of $\gamma\gamma$ and $e\gamma$ data analysis, except when the measurement had superposition with other lines as indicated in column SL. We have also enough statistics to extract experimental b_2 particle parameters for the transitions 605*K* and 795*K*. They are obtained by the relationship $b_2=A_{22}(e-\gamma)/A_{22}(\gamma-\gamma)$. We have five cascades that can be used to find b_2 for the 605*K*. We disconsidered the 795–605 *K* because the 605*K* should be separated from $569_{L,M}$ taking out the β^- background. Averaging for the four cascades left, we have $b_2(605K)=1.31(28)$, that is in good agreement to the theoretical value $b_2=1.42$ interpolated from Hager and Seltzer tables [12]. The transition 569–795 *K* gives $b_2(795K)=0.131(25)/0.1087(21)=1.20(23)$, when we considered the 795 keV as a pure $E2$ transition. This is also in good agreement with the theoretical value $b_2=1.31$. If we use this theoretical particle parameter, we can even infer the multipole mixing ratio in the 569γ transition. To obtain δ in the fitting procedure, instead of the usual α_0, A_{22}, and A_{44} fit, a direct least-squares search for α_0 and δ [13] was performed, i.e., we took into account the constraint between A_{22} and A_{44}, while minimizing χ^2. This gives $\delta_{569}(E2/M1)=0.274(44)$, with $\chi^2=0.70$, in agreement with the value 0.226(9) obtained in the $\gamma\gamma$ measurements [7].

The 563 keV transition also has the possibility of an $E0$ [14–16] decay mode competing with $E2$ and $M1$ [4], since it is a $2^+\rightarrow 2^{+\prime}$ decay. Using our experimental result $A_{22}=-0.240(94)$ for the cascade and dividing by the theoretical A_2 from the second transition (-0.5976) we get $B_2=0.40(15)$. To get this result from the theoretical expression [17] for B_2, we have estimated [7] that $q_K^2(E0/E2)\equiv\langle E0\rangle_K^2/\langle E2\rangle_K^2\leqslant 0.06$.

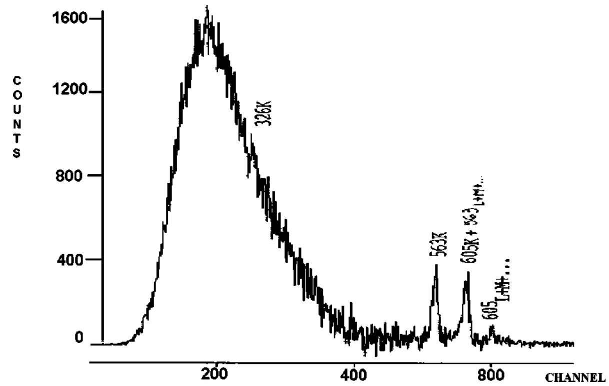

FIG. 2. Electron spectrum for the 475 keV γ window obtained adding measurements done at several angles.

Comparing the $\gamma\gamma$ and $e\gamma$ measurements we saw that the $\gamma\gamma$ gave, in general, a much better precision in the multipolar mixing ratios.

We can also extract ICC from the $e\gamma$ measurements. The detector efficiency does not have strong changes in this range [18] and we can extract the 795*K* electron conversion ratio from our measurements combined with other results from the expression

$$\begin{aligned}\alpha_{795K}\equiv\frac{I_{795K}}{I_{795\gamma}}&=\left(\frac{I_{569\gamma-795K}}{I_{569\gamma-605K}}\right)\times\left(\frac{I_{569\gamma-605\gamma}}{I_{569\gamma-795\gamma}}\right)\times\left(\frac{I_{605K}}{I_{605\gamma}}\right)\\&=\left(\frac{1671(21)}{3225(42)}\right)\times(1)\times(5.03\times10^{-3})\\&=2.59(5)\times10^{-3},\end{aligned} \tag{2}$$

where $I_{605K}/I_{605\gamma}=\alpha_{605K}=5.03\times10^{-3}$ was taken from the theoretical value quoted by Chand [2]. Our value of α_{795K} is in better agreement with the theoretical result 2.58×10^{-3} [2] for pure $E2$ than the earlier result $2.71(10)\times10^{-3}$ [2] obtained from single electron spectra, probably because in the coincidence method the 569γ window acts as a filter thus ''cleaning'' the electron spectrum, reducing background and superposition from neighbor lines. Using the relative intensities measured by Wang *et al.* [19], we also extracted the 802*K* conversion coefficient as $\alpha_{802K}=2.66(8)\times10^{-3}$, in agreement with the theoretical $2.56(4)\times10^{-3}$ and experimental $2.49(12)\times10^{-3}$ quoted [2]. We also tried to extract the ICC from other cascades but they have large errors and have superposition of other lines.

We identified for the first time *K* electrons from the 326 keV transition. The 326*K* line is highly hidden in the β spectrum. It was only distinguishable from the background when we added the spectra of the seven angles measured and we made a window in the 475 keV γ (Fig. 2). An energy calibration was made with 475*K*, 563*K*, 569*K*, 1038*K*, 1168*K*, and 1365*K* using cuts where these lines were free. The theoretical energy value for the 326*K* is $E_{326K}=326.5-37.4=289.1$ keV, where the data from the γ energy and the *K* shell were taken from Lederer and Shirley [20]. With this calibration, at the 475 keV γ window, we found a line at

287.7(11) keV and area of 502(221) counts. In the same window, the adjusted area in the $605K$ line was 2272(147) counts. Using the same method described above we can estimate the ICC for the 326 keV transition, giving

$$\begin{aligned}\alpha_{326K}=\frac{I_{326K}}{I_{326\gamma}}&=\left(\frac{I_{326K-475\gamma}}{I_{475\gamma-605K}}\right)\times\left(\frac{I_{475\gamma-605\gamma}}{I_{326\gamma-475\gamma}}\right)\times\left(\frac{I_{605K}}{I_{605\gamma}}\right)\\ &\simeq\left(\frac{502(221)}{2272(147)}\right)\times\left(\frac{2.497(13)\%\times 82.4(3)\%}{27.28(6)\%\times 0.059(6)\%}\right)\\ &\quad\times(5.03\times 10^{-3})\\ &\simeq 14(6)\times 10^{-2}.\end{aligned}\tag{3}$$

The theoretical values for the lowest multipolarities are $\alpha_{326K}(E2)=2.7\times 10^{-2}$ and $\alpha_{326K}(M1)=3.1\times 10^{-2}$, interpolated from [12]. The discrepancy led us to conclude that this is a preliminary result and a better resolution of the electron detector could eventually achieve more confident results.

The particle parameters in the 605K and 795K transitions in electron-γ measurements agree with the theoretical values. An upper bound for the $E0/E2$ mixing was estimated for the 563 keV transition by $e\gamma$ interference method giving $q_K^2 \leqslant 0.06$. We developed a method of extracting ICC from electron-γ correlation measurements and obtained $\alpha_{795K}=2.59(5)\times 10^{-3}$ and $\alpha_{802K}=2.66(8)\times 10^{-3}$, both in agreement with previous data and theoretical values [2]. By this method we obtained $\alpha_{326K}\simeq 14(6)\times 10^{-2}$, about one order of magnitude higher than the expected theoretical value. A better resolution could eventually confirm or discard this preliminary result.

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