INTENSITIES OF MESONIC 2p-1s X-RAYS IN N, ^{16}O , ^{18}O , F, AND Na

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ABSTRACT

The yields of pionic and muonic 2p-1s X-rays are given for N, ^{16}O , ^{18}O , F, and Na. The populations of the pionic 2p levels are determined and the natural widths are deduced.

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The measurement of the pionic 2p-1s X-ray intensity per pionic atom Y_π , yields information about the strength of the absorptive interaction between the pion in the 2p level and the nucleus. Earlier measurements of pionic X-ray intensities with scintillation counters were performed by Camac et al.¹⁾ and Stearns and Stearns²⁾. We have been able on the basis of more precise intensity measurements and detailed studies of the cascade process to deduce 2p level widths $\Gamma(2p)$ for light nuclei. This extends the $\Gamma(2p)$ data obtained from the 3d-2p transitions^{3,4)} to lower Z elements for which also the 1s level widths are available⁹⁾. The measurements described here were made at the muon channel of the CERN 600 MeV synchro-cyclotron. Preliminary data have been reported previously⁵⁾. The experimental set-up has already been described⁶⁾. The targets consisted of NaN_3 , N_2^{16}O , H_2^{18}O , LiF, and metallic Na. The X-rays were measured with a Ge detector with an active volume of $3.2 \text{ cm}^2 \times 0.8 \text{ cm}$. The energy resolution was 1.4 keV at 120 keV. Each target was measured both in the pionic and muonic beam.

The natural width Γ of a level - full width at half maximum of the Lorentzian absorption line - is related to the absorption rate W_a by

$$\Gamma = \hbar W_a .$$

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A direct measurement of the 2p level width $\Gamma(2p)$ from the line shape is possible at higher Z values only^{3,4)} where the natural level width $\Gamma(2p)$ is not negligible in comparison with the instrumental line width. All experiments of this paper were concentrated on the determination of $W_a(2p)$, the absorption rate from the 2p level. Several experimental methods were applied to obtain $W_a(2p)$.

The absorption rate $W_a(2p)$ is connected with the 2p-1s X-ray rate W_X , the corresponding Auger rate W_A , the 2p level population $P(2p)$ and the 2p-1s X-ray yield Y_π per pionic atom by

$$W_a(2p) = W_X \left[P(2p)/Y_\pi - 1 \right] - W_A .$$

W_X and W_A were calculated using a program written by J. Hüfner⁷⁾.

For the two nuclei ^{23}Na and ^{19}F the ratio $P(2p)/Y_\pi$ could be directly measured by summing up all transitions populating the 2p level and comparing them with the 2p-1s intensity. Common factors such as the number of pionic atoms formed per unit time immediately cancel. In all other cases, $P(2p)$ and Y_π had to be determined separately by indirect methods, essentially by comparison with muonic transitions. For ^{19}F and ^{23}Na both methods were applied.

The X-ray yield of the muonic 2p-1s transition, Y_μ , is obtained under the assumption that the quantum intensity of the entire K-series (2p-1s, 3p-1s, etc.) plus the small percentage of muons feeding the 2s level amounts to 100%. The 2s level population was calculated by the cascade program⁷⁾. The experimental values of Y_μ are given in Table 1, column 1, and are equal to the population values of the muonic 2p level. From the muonic population the pionic population cannot be obtained immediately, since the cascade process depends on the energies of the levels and differs for pions and muons⁸⁾. In column 2 the calculated Y_μ are given assuming a statistical population $P(n, \ell) \propto (2\ell + 1)$ for $n = 14$ as an "initial distribution". The observed variation with Z cannot be obtained with this assumption and an additional parameter is necessary to match the data. This was done in two ways: (1) The population of the highest ℓ -state at $n = 14$ was enhanced by a constant a_ℓ such that

$$P(n, \ell) = (2\ell + 1 + a_{\ell}) / \sum_{\ell=0}^{n-1} (2\ell + 1 + a_{\ell})$$

with $a_{\ell} = 0$ for $\ell < n - 1$ and $a_{\ell} = \text{free}$ for $\ell = n - 1$. The values of a_{n-1} which fit the muonic cascade (2p-1s through 7p-1s) best are given in column 4 and the corresponding Y_{μ} are listed in column 3. (2) In the second method a distribution at $n = 14$ with $a_{n-1} = 0.80$ was assumed for all nuclei and a parameter f was chosen individually for each target by which the calculated 2p-1s transition intensity has to be multiplied in order to agree with the measured one. The values for f are given in column 5. The pionic cascade has now been computed starting with $n = 18$ and using the same "initial distribution", i.e. the same a_{n-1} or f values as found from the muonic cascade. This results in the $P(2p)$ values listed in Table 2, column 1 and 2, respectively. The mean values used for further calculations are given in column 3.

The pionic yield Y_{π} was determined using the muons present in the pion beam. Both pionic and muonic spectra appear simultaneously during a pionic run. The ratio between muons and pions stopped in the target was determined in three different ways (Table 3): (a) The target was replaced by a plastic scintillation counter of approximate target size, and the number of muons was measured via the decay electrons. The counter was connected with a time-to-pulse height converter which was started by a signal from a particle stopped in the plastic counter and was stopped by a second signal from the counter in anticoincidence with the telescope. (b) A second method made use of a direct intensity comparison between muonic and pionic lines in cases where neither Auger transitions nor nuclear absorption are appreciable: 4f-3d transitions in elements with $24 \leq Z \leq 30$. The yields of the observed lines were calculated by the cascade program⁷⁾ which did not show significant differences between muonic and pionic atoms for these elements. (c) The third method consists of an extrapolation of the muonic peak of the total range curve down to the pionic peak; it was assumed that both individual range curves are of similar shape.

The intensities were evaluated by a best fit program as described in Ref. 9 and corrected for the density distribution of the stopped

particles, absorption in the target and counter efficiency. The yields Y_{π} thus obtained are listed in Table 2, column 4. In the cases of the NaN_3 and LiF targets corrections were applied for the different capture of pions and muons in the two constituents of these chemical compounds.

The 2p level widths deduced from both the "direct" method and the indirect methods for the determination of $P(2p)$ and Y_{π} are given in Table 4, column 1 and 2, respectively. The quoted errors of column 2 include an estimated error of 10 per cent for $P(2p)$. Column 3 lists the final results of this paper. In the cases of Na and F this is the mean of column 1 and 2.

A comparison with earlier experimental work^{3,4)} is difficult and reasonable only for the yields Y_{π} . The authors measure in the first place the total yield of the entire K series. In Table 4, column 5, the Y_{π} values of Camac et al.³⁾ are quoted. In column 6 we have given values which we obtained from data of Stearns et al.⁴⁾ using their yield of the total K series and their estimate of the fraction of the 2p-1s line. The agreement is fair except in the case of N where a real discrepancy exists.

It is a great pleasure to thank J. Hüfner for putting his cascade program at our disposal.

TABLE 1

Muonic yields and parameters of the "initial distribution"

	Muonic 2p-1s yields Y_{μ} (per cent)			Parameters	
	Experiment	Computed with $a_{n-1} = 0$	Computed with adapted a_{n-1} (column 4)	a_{n-1}	f
	1	2	3	4	5
N	63 ± 2	52	63	0.30	0.86
^{16}O	58 ± 2	53	57	0.10	0.78
^{18}O	56 ± 3	53	55	0.05	0.76
F	70 ± 2	54	70	0.50	0.94
Na	76 ± 2	56	76	0.80	1.00

TABLE 2

Pionic populations and yields

	2p level populations P(2p) (per cent)			Pionic 2p-1s yields Y_{π} (per cent)		
	with a_{n-1} of TAB. 1, col. 4	with f of TAB. 1, col. 5	Mean value	This work	Ref. 3	Ref. 4
	1	2	3	4	5	6
N	62	62	62	6.8 ± 0.8	4.0 ± 0.8	3.4
^{16}O	57	58	57	4.9 ± 0.7	3.1 ± 1.0	3.4
^{18}O	55	56	55	5.6 ± 0.8		
F	70	70	70	6.1 ± 1.0		4.1
Na	78	78	78	3.3 ± 0.7		

TABLE 3

Ratio μ/π under π peak (per cent)

Method	μ/π
μ -decay	6.8 ± 0.4
4f-3d transitions	6.6 ± 0.8
range curve	9.0 ± 2.0
mean value	6.8 ± 0.4

TABLE 4

2p level widths $\Gamma(2p)$ (in eV)

	"Direct" method	"Indirect" method	Mean value
	1	2	3
N		2.2 ± 0.3	2.2 ± 0.3
¹⁶ O		4.9 ± 0.8	4.9 ± 0.8
¹⁸ O		4.1 ± 0.7	4.1 ± 0.7
F	8.2 ± 1.5	7.7 ± 1.5	8.0 ± 1.3
Na	42.6 ± 10.0	37.0 ± 8.8	39.5 ± 8.6

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