Muon capture through bonding electrons in pure silicon

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The muonic x-ray intensities of the Lyman series in pure silicon are investigated. The fitted data are compatible with a statistical initial angular momentum distribution of the captured muons. From a comparison with data measured in diamond, cubic boron nitride and in the two isoelectronic series F^-,Ne,Na^+ and Cl^-,Ar,K^+, we conclude that the calculated muon distribution reflects the symmetry of the electrons through which muon capture proceeds.

The numerous experimental results on muon and pion capture in compounds and mixtures of elements[1] strongly indicate that the chemical bond between the elements influences the atomic capture of negative particles. Therefore one can expect that the atomic capture ratios measured in compounds give information on the spatial distribution of bonding electrons. In two recent papers, Imanishi *et al.*[2] deduce from atomic capture ratios for pions measured in beryllium and boron compounds net atomic charges on the bond partners. Qualitative agreement is obtained with theoretical predictions. However, general correlations between muonic x-ray intensity patterns and electronic structures could not yet be mathematically formulated. First attempts have been made to connect measured muonic $K\beta$-to-$K\alpha$ intensities in pure elements and in their oxides and chlorides to their electronic structures.[3] In a study of iron compounds, Naumann *et al.*[4] observed significant differences in the muonic x-ray intensity patterns, which are correlated to the structure of the outer iron electrons in these compounds.

In a recent paper,[5] we have shown that negative muons, captured into the Coulomb field of a nucleus via electrons of full $(2s,2p)$ or $(3s,3p)$ shells, have the same "initial" angular momentum distributions. More precisely, the muonic x-ray intensities measured in F^-, Ne, Cl^-, Ar, and K^+ can be reproduced by a cascade calculation,[6] starting at a muon atomic level $n=14$, by assuming a statistical initial distribution. According to the Fribourg version[7] of the model of large mesic molecules, this statistical distribution is correlated to the spatial structure of the electrons through which the muons are assumed to be captured. However, the muonic x-ray intensities measured in Na^+ cannot be reproduced by assuming a statistical initial angular momentum distribution of the captured muons.[5] The model[7] explains this observation by the absence of participation of the $2s$ electrons in the muon capture mechanism.

If the interpretation of the measured muonic x-ray intensities in Ref. 5 is correct, one expects to find statistical initial distributions also in carbon and silicon in diamond structure. Indeed, according to Ref. 7, muon capture should proceed there exclusively via bonding electrons, the spatial structure of which is essentially given by hybridization of the $2sp^3$ or $3sp^3$ orbitals, and exhibits the same symmetry as full atomic $(2s,2p)$ or $(3s,3p)$ shells, respectively.

The present paper reports on a new measurement of relative intensities of the muonic Lyman series in pure silicon of cubic structure and compares them with cascade calculations. In earlier papers[8,9] we reported on measurements and analyses of muonic x-ray intensities in carbon of diamond and graphitic structures and in nitrogen of boron nitride in cubic and hexagonal structures.

Our measurements were performed at the superconducting muon channel of the Swiss Institute for Nuclear Research (SIN) in Villigen. The experimental setup, the data acquisition system, and the data analysis were simi-

TABLE I. Lyman-series intensity ratios in pure silicon. All values have been multiplied by 10^3.

Ratio	This work	Suzuki[a]	Mausner *et al.*[b]	Bergmann *et al.*[c]
I(3-1)/I(2-1)	96.0±3.4	105±11	82±3	92.3±2.5
I(4-1)/I(2-1)	55.7±2.0	42±8	48±2	
I(5-1)/I(2-1)	48.2±1.8		35±2	
I(6-1)/I(2-1)	30.3±1.2		22±1	
I(7-1)/I(2-1)	15.0±0.6	117±29	8±1	
I(8-1)/I(2-1)	5.1±0.3			
I(R-1)/I(2-1)	8.3±0.5			

[a]Reference 10.
[b]Reference 11.
[c]Reference 12.

TABLE II. Comparison of experimental and calculated muonic Lyman-series intensities assuming a statistical and a modified statistical angular momentum distribution $P(l) \propto (2l+1)\exp(\alpha l)$, for $n=14$.

Transition	Experiment	Calculation $\alpha=0$	Calculation $\alpha=0.012$
2-1	0.7945±0.0190	0.7875	0.7958
3-1	0.0763±0.0020	0.0763	0.0748
4-1	0.0443±0.0012	0.0460	0.0443
5-1	0.0383±0.0011	0.0410	0.0390
6-1	0.0240±0.0008	0.0260	0.0245
7-1	0.0120±0.0004	0.0121	0.0112
8-1	0.0041±0.0002	0.0046	0.0042
R-1	0.0065±0.0004	0.0065	0.0060
χ^2		3.5	1.0

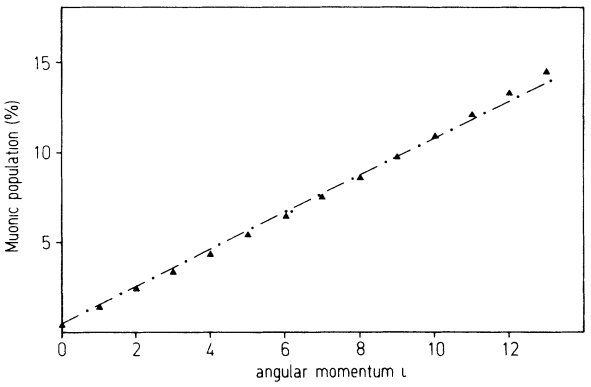

FIG. 1. Calculated muon angular momentum distribution in silicon (closed triangles) for a muonic atom level $n=14$ obtained by a fit of the measured muonic Lyman-series intensities. The distribution was assumed to be a modified statistical one, $P(l) \propto (2l+1)\exp(\alpha l)$, with $\alpha=0.012$. The dot-dashed line corresponds to a purely statistical distribution ($\alpha=0$).

lar to those of earlier experiments.[8] Regarding the target, chemically pure powdered silicon of thickness 1 g/cm^2 and pressed in a beryllium box was used.

Muonic x-ray intensities in pure silicon have been measured before.[10–12] However, the results scatter rather broadly, and only Mausner *et al.*[11] have measured the K series up to the 7-1 transition. Hence we have remeasured the Lyman-series intensities including the 8-1 transition and the K-series edge. Table I compares the muonic x-ray intensity ratios of the Lyman series as measured by the different authors with our data. While Bergmann *et al.*[12] and Suzuki,[10] the latter with rather large error bars, are in reasonable agreement with our data, the intensity ratios of Mausner *et al.*[11] are consistently lower. Using the cascade calculation[6] with two adjustable parameters, namely, a parameter α for the distribution over angular momentum states and the electronic K-shell refilling width Γ_K, we have fitted our seven independent intensity ratios. Table II shows the comparison of the measured muonic x-ray intensities with the fitted ones. Other fits have been performed starting at principal quantum numbers $n=16$ and 18, with the same electronic K-shell refilling width $\Gamma_K=0.18$ eV. In these cases the fitted values of the parameter α were 0.008 and 0.016, respectively, with an equally good agreement between the measured and the fitted intensities as when starting at $n=14$.

Figure 1 shows a comparison of our fitted angular momentum distribution in silicon ($\alpha=0.012$) with a purely statistical distribution ($\alpha=0$). Although the latter yields a χ^2 value of about 3, i.e., a factor of 3 larger than the fitted distribution, we do not consider the deviation to be significant (cf. Table II). Thus we are in the same situation as in carbon and in nitrogen of boron nitride in cubic structures,[8] where the fitted initial distributions of the captured muons were even closer ($\alpha=0.005$ and -0.002, respectively) to the statistical distribution.

So we have shown that muons captured via bonding electrons of spatial symmetries similar to full $(2s,2p)$ or $(3s,3p)$ shells have the same initial angular momentum distributions.

As already shown in Ref. 5, identical initial angular momentum distributions in different elements do not yield identical muonic x-ray intensities. Direct comparison of muonic x-ray intensities,[12–15] although useful, will not show similarities in the capture mechanism such as those revealed through initial distributions. In silicon and diamond for example, the muonic $I(K\beta)/I(K\alpha)$ intensity ratio differs by almost a factor of 3, whereas the initial angular momentum distributions are identical.

Atomic muon capture has not yet revealed its detailed mechanism despite the numerous experimental data available today on capture ratios and muonic x-ray intensities. Capture ratios alone seem unable to provide a decisive cut among the different models for the muon capture. Together with the fitted initial angular momentum distributions in selected elements of compounds, however, notable progress should become possible in the understanding of the formation mechanism of exotic atoms.

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