E546: Measurement of Electronic X rays correlated with Pionic X rays
E567: Precise Measurement of Electronic X rays from pionic atoms

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1. Introduction

Our goup (pAX) has been studying the negative pion capture process on molecules for the creation of new chemistry by the 2nd generation substance consisting of muonic and/or pionic atoms. In our previous project (E262 and E360), we studied the pion capture process on hydrogen containing molecules in liquid and gas phases. The LMM model combined with a pion transfer process was confirmed by the experimental results based on the mesurements of pionic X rays and neutral pion decays [1]. Negative pions exist in highly excited states at the beginning of the capture process, and then they cascade down to lower excited states by emitting pionic X rays or Auger electrons. Auger electron emission is followed by electronic X-ray emission from pionic atoms. Since the pion mass is about 270 times as large as the electron mass, pionic orbitals have small radii; the pion strongly shields the orbital electrons from the nuclear charge. Therefore characteristic X-ray energies of pionic atoms are not those of the target atom (atomic number Z) but close to those of Z-1 atom, and include information on the electronic rearrangement in the pion capture process.

In this project, we planned to examine electronic X-ray emission rates correlated with each pionic X ray and to measure precisely the energies of electronic X rays to understand electron rearrangement during the pionic cascade in pionic atoms.

2. Experimental

The measurements were performed at πμ-channel of KEK-PS. As illustrated in Fig. 1, the measuring system consisted of four plastic scintillation counters and three Ge detectors. The target chamber was filled with He gas to reduce background. The signals from Ge detectors were taken in coincidence with the stop events by PS1, PS2, PS3 and veto PS4. To examine the correlation between pionic X rays and electronic X rays, the photon events are recorded in a list mode. We used metal foils of Copper to Uranium (Z = 29 to 82) and the some compounds as the targets. Executed beam times were 03-6-1 (30 shifts) for E546 and 05-1/05-4-2 (30+15 shifts) for E567. The measured samples and the beam conditions are summarized in Table 1.

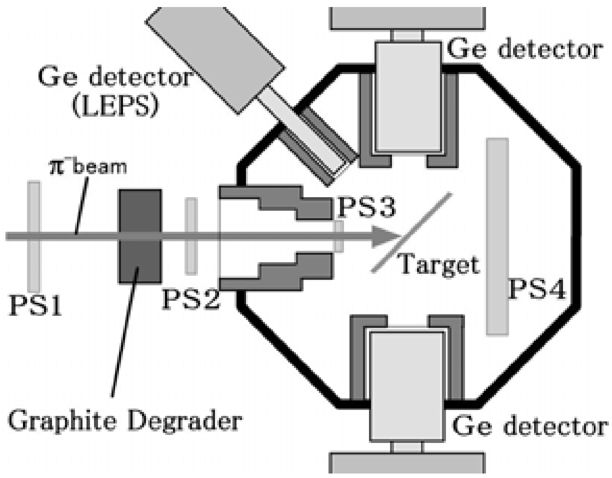

Fig. 1. Schematic drawing of experimental setup at πμ-channel.

Table 1. Measured samples and the beam conditions.

Target	atomic number	Thickness (g/cm^2)	total STOP event /10^6	Target	atomic number	Thickness (g/cm^2)	total STOP event/10^6
Cu	29	0.179	126	Ho_2O_3	67	0.530	64
Zn	30	0.143	112	Er_2O_3	68	0.577	161
Mo	42	0.051	120	Tm_2O_3	69	0.587	166
Ag	47	0.210	148	Yb_2O_3	70	0.488	93
Sn	50	0.073	170	Lu_2O_3	71	0.621	127
NaI	53	0.806	235	Hf	72	0.665	233
Xe	54	1.09	113	Ta	73	0.333	40
CsF	55	0.834	244	W	74	0.386	48
BaO	56	0.622	208	Ir	77	1.13	101
Eu_2O_3	63	0.294	109	Au	79	0.578	68
Tb_4O_7	65	0.491	93	HgO	80	0.688	130
Dy_2O_3	66	0.516	116	Tl_2O_3	81	0.356	151
Gd_2O_3	64	0.449	82	Pb	82	0.340	55
Ho	67	0.220	23	$UO_2(ac)_2$	92	0.574	356

3. Results and discussion

Obtained X-ray spectrum for a Mo target is shown in Fig. 2. Al pionic X rays were observed due to aluminum chamber, and electronic X rays of Mo were caused by ionization with fast pions. We tried to measure the electronic X rays emitted from each excited state of a pionic atom. However, the number of correlated events is too small to discuss the difference in the electronic X-ray energies between pionic states quantitatively.

First, we examined electronic KX-ray structure of pionic atoms and compared between those for metal and oxide samples. There is no much difference among coincidence spectra that is gated by various pionic X rays. Although the number of the correlated events is small, in low Z region the yield ratio of electronic K_α to K_β X ray in oxide target is clearly larger than that of metal targets as shown in Fig. 3. These difference of K_βX ray would be caused by the difference in electron population in pionic atom between metal and oxide targets. Assuming that it arises from the difference in the electron configuration and the pion state at the moment a negative pion was captured, we are examining the observed chemical effect by means of theoretical calculations described below.

Next, we used the gross spectrum to obtain the energy shifts of the electronic X rays. The result of the spectrum analysis for Gd target is shown as an example in Fig 4. One can find clear energy difference between characteristic X rays of pionic Gd atoms (measured in the beam experiment) and those of Eu atoms (Z-1 atom). The energy shifts were found in both K_α and K_β lines of other targets. The energy shifts observed for Z = 30 to 82 are shown as a function of the atomic number in Fig. 5. The energy shift of the pionic atom becomes smaller with increasing atomic number on the whole. According to the relationship between the electron K-shell binding energy and the pionic X-ray energy, for the low-Z targets (Z < 65), the electronic KX-ray emission, induced by the Auger process, starts when the pion reaches the n = 8 or smaller n state (n is the principal quantum number). On the other hand, it occurs

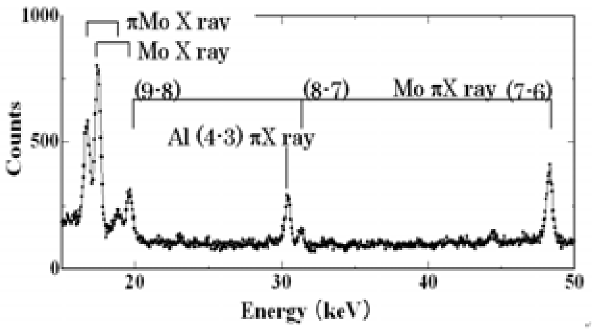

Fig. 2. Observed X-ray spectrum for Mo target. The numbers in parentheses indicate the main quantum numbers relevant to the pion transition.

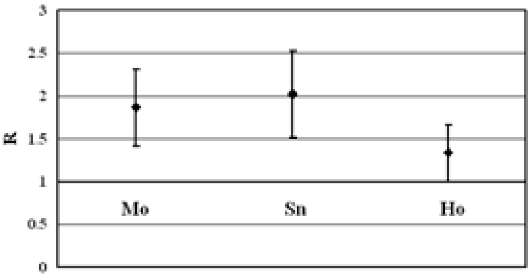

Fig. 3: Comparison of the yield ratio of electronic K_α to K_β X ray between metal and oxide targets correlated with various pionic X rays.
R = (K_β/K_α ratio of M) / (K_β/K_α ratio of M_lO_k)

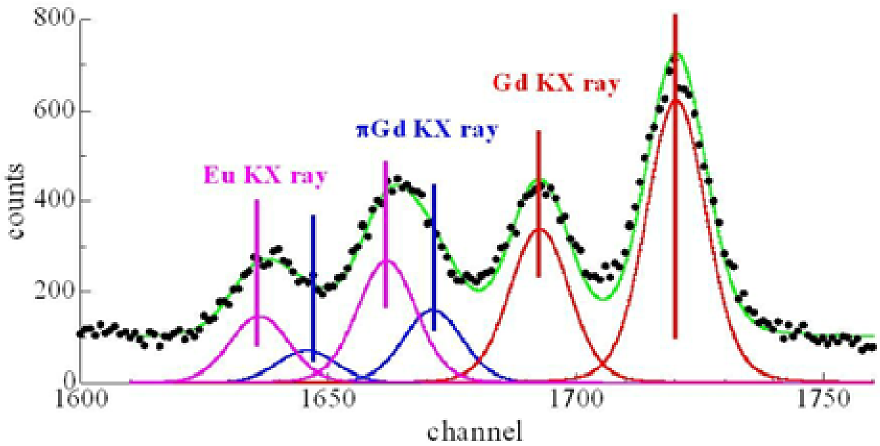

Fig. 4. Electronic X-ray spectrum for pionic gadolinium with its fitting lines. Dotted and dashed dotted lines means characteristic X-ray lines for Z and Z-1 atoms, respectively. Solid lines indicate the electronic X-ray peaks for pionic atom.

when the pion reaches the n = 7 or deeper state, for high-Z targets (Z > 65). In the latter case, the energy shift becomes smaller than that in the former case, because the pion screens the nuclear charge more strongly as it exists in a smaller principal quantum number state. Thus, we can qualitatively explain the tendency of the energy shift by the screening effect. [2] In the actual process, when electronic X-rays of pionic atoms are emitted, the pions exist in various orbits and thereby cause different screening effects. Therefore, the observed X-ray peak consist of complex lines with various energy shifts. Similar measurements were performed for muonic atoms at KEK-MSL.[3]

In this study, two calculations were performed to obtain more detailed information on the atomic electronic states in the pion cascade. One is the calculation on cascading process of pion or muon, and another is the calculation on the energy levels of atomic electrons for pionic or muonic atom. The aim of the former calculation is to estimated the pion or muon distribution at the electronic KX-ray emission. The latter is carried out to reveal the electronic X-ray energies of such pionic or muonic states and of those states with various electron structures. The modified Akylas-Vogel [4] cascade code was used for the former calculation. The original code had been written to reproduce only a muonic cascade. In modified version,

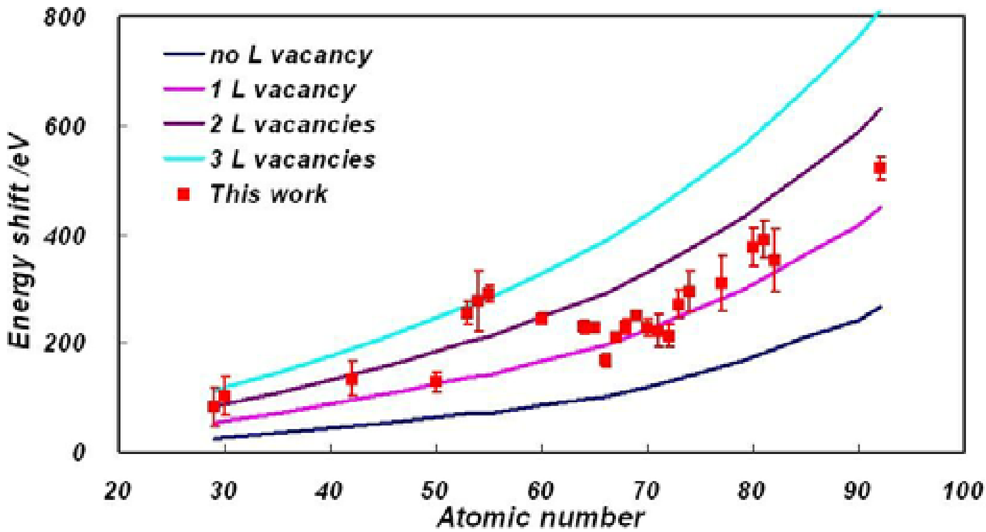

Fig. 5. Comparison of the energy shift for pionic atom between experimental and theoretical values. Experimental results are shown by closed squares. Lines indicate the theoretical values with no and various L-electron vacancies.

the effect of strong interaction was introduced to apply to a pionic cascade. We can estimate the K-hole distribution created by Auger process in the pion cascade calculation using the optimized parameters for the pionic X ray intensities. The latter calculation was performed by using the remodeling single configuration Dirac-Fock code[5]. In our code, pion or muon orbital is taken in the density of nuclear charge. Electron binding energies are calculated on not only various pionic state when K-electron Auger process occurs but variety number of L-electron vacancies. Figure 5 shows a comparison between the observed and calculated energy shifts. One can see that one or two L-electron vacancies exist during the pion cascade for pionic atoms in the low Z region. More detailed analysis and discussion are in progress for dynamic inner shell process.

References

[1] A. Shinohara, et al., Phys. Rev. A. **53**, 130(1996); A. Shinohara, et al., Phys. Rev. Lett., **76**, 2460 (1996).
[2] K. Ninomiya, et al., Radiochimca Acta. **93**, 515-518(2005).
[3] K. Ninomiya, et al., J. Radioanal. Nucl. Chem., **272**(3), 661-664 (2007).
[4] V. R. Akylas et al., Comput. Phys. Commun., **15**, 291 (1978).
[5] A. L. Ankudinov et al, Comput. Phys. Commun., **98,** 359 (1996).