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Concentration dependence of Coulomb capture of muons in noble gases

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The Coulomb capture of muons has been measured in gaseous Ne, Ar, and Kr mixtures. A concentration dependence of the per atom capture ratio was established for the first time.

The per atom Coulomb capture ratio $A(Z_1,Z_2)$ of muons in the two constituents of a homogeneous mixture or a chemical compound with atomic numbers Z_1 and Z_2 is usually assumed to be independent of the respective atomic ratio k_1/k_2. The question whether this assumption is justified has rather lately been recognized to be not at all trivial.[1]

No pronounced k_1/k_2 dependence may be expected for condensed matter because the shape of the spectral flux density $n(W)$ of the muons in the target at energy W is not expected to depend strongly on the target material,[2–4] the physical reason being, finally, the small atomic size and hence steep electronic potential. The possible effect of a variation of $n(W)$ on $A(Z_1,Z_2)$ has very recently been treated in the semiclassical theory.[5] The first experiment on concentration dependence[6] was apparently performed rather late, compared to experiments on Z dependence. Here, and in two more recent condensed state experiments,[7,8] no k_1/k_2 dependence was observed although in the latter the atomic ratio was varied over a very wide range.

Due to the great differences in radius and hence in electron density in the outer region of the atom, however, Coulomb capture in gases differs strongly from that in condensed matter.[4] In particular, there is no more reason to assume the shape of $n(W)$ *not* to vary with k_1/k_2. Although capture experiments with gases have already been performed (Refs. 9 and 10, and references quoted therein), there is up to now no experiment on concentration dependence in the gaseous phase.

In order to investigate the problem experimentally we measured $A(Z_1,Z_2)$ in binary and ternary mixtures of noble gases at medium pressure and room temperature. The mean distance between two neighboring gas atoms in the case of highest density occurring in our experiment was calculated to 8.90 Å, while the radial expectation value of an outer-shell electron of the largest atom Kr amounts to 1.04 Å.[11] So any mutual influence will be small. Therefore the Coulomb capture cross section $\sigma(W)$ of a noble gas for a muon of energy W is not expected to depend on admixtures of other noble gases in the pressure region of our experiment. Any variation of $A(Z_1,Z_2)$ with k_1/k_2 may hence be attributed to a change in the shape of $n(W)$.[5,12] The experiment was performed at the μ channel I of the Schweizerisches Institut für Nuklearforschung (SIN), Villigen, Switzerland. Binary mixtures of Ar and Ne and of Kr and Ar were investigated at a total pressure of 51 bars (cf. Table I). Furthermore, binary mixtures of Kr and Ne (pressure 16 bars) were first measured and, later, ternary mixtures of the same Kr-Ne content plus Ar added up to 51 bars total pressure (cf. Table II). The atomic ratios are given as ratios of the absolute concentrations in atomic percent and were deduced from the respective measured values of pressure and temperature by solving the van der Waals equation with coefficients taken from Ref. 13 and applying the formulas for gas mixtures.[14] The gas vessel consisted of an Al cylinder of 200 mm length, 73 mm inner diameter, and 3.5 mm wall thickness. The Al front and end plates were 7.5 mm thick. Two Ge detectors were used simultaneously: a hyperpure Ge detector of 25 cm^3 [in-beam resolution 1.06 keV full width at half maximum (FWHM) at 272 keV] and a Ge(Li) detector of 67 cm^3 (in-beam resolution 1.58 keV FWHM at 815 keV) for the lower and upper parts of the muonic x-ray spectrum, respectively. By varying the degrader thickness and measuring the intensity of the main gas x-ray line, the stopping distribution was for each run positioned in the target center. The spectra were taken in prompt and delayed coincidence with a scintillation counter telescope. Figure 1 shows a prompt spectrum.

In all runs at 51 bars, the FWHM value of the stopping distribution along the beam direction was

TABLE I. Comparison between binary mixtures. In the last column, $A(Z_1,Z_2)_{norm}$ is the measured value of run 1 in the cases of runs 2 and 3 and of run 4 in the cases of runs 5 and 6, respectively. Z_1 = Ar and Z_2 = Ne for runs 1 through 3, and Z_1 = Kr and Z_2 = Ar for runs 4 through 6. Total pressure always 51 bars.

Run	Z_1/Z_2	k_1/k_2	$A(Z_1,Z_2)$	$\frac{A(Z_1,Z_2)}{A(Z_1,Z_2)_{norm}}$
1	Ar/Ne	79.2/20.8	1.23 ±0.02	1.00
2	Ar/Ne	50.3/49.7	1.01 ±0.03	0.83 ±0.02
3	Ar/Ne	20.2/79.8	0.91 ±0.04	0.74 ±0.04
4	Kr/Ar	79.5/20.5	2.67 ±0.16	1.00
5	Kr/Ar	50.0/50.0	2.26 ±0.05	0.85 ±0.05
6	Kr/Ar	21.0/79.0	1.76 ±0.03	0.66 ±0.04

about equal to the area thickness of the target gas. As the beam is rather well focused, the target walls did not give rise to a disturbing background, in particular, not for the elements heavier than Al, the main element visible in the background spectrum. The background could, moreover, be well determined as its spectrum was almost the same for all gas fillings. Its relative intensity was higher for the 16-bars runs; hence the errors due to background subtraction could be appreciable here. In the worst case, run 7, the intensity ratio Ne(2-1)/Al(2-1) was 0.0720 ±0.0011. The intensities of nuclear γ rays were derived from the delayed spectra.

After background subtraction, the x-ray intensities were corrected for absorption in the target gas and in the wall of the vessel, and also for the detector efficiency. In the case of Kr-Ar, the contributions of Kr lines interfering with Ar lines were calculated from other unmasked components, taking fine-structure splitting into account. The capture ratios were obtained from the sum of the Lyman series intensities in the components.

The experimental results are summarized in Tables I and II. The values given in the $A(Z_1,Z_2)$ column contain the statistical errors of the line intensities, the errors of the detector efficiencies, and the errors of the absorption in the gas and the target wall. The ratios $A(Z_1,Z_2)/A(Z_1,Z_2)_{norm}$ show more clearly the variation with k_1/k_2, in particular, because their errors are smaller due to cancellation of some of the input quantities (and their uncertainties) common to the two runs that are combined to give each ratio. Details of the error computation are given in the thesis of Ehrhart.[15]

The present experiment is the first one to establish a concentration dependence of the per atom μ capture ratio in any compound or homogeneous mixture. With respect to the concentration dependence, it does not disagree with any previous experiment. In the case of Ar-Ne mixtures, the absolute numbers for $A(Z_1,Z_2)$ do not agree well with recent work[9] although they are strictly not comparable due to different pressure and uncertainties on the concentration. All results in the binary gas mixtures and those in the ternary mixtures of runs 7 and 8 can be qualitatively described in the same way: the higher the average weight or Z of the gas, the greater becomes $A(Z_1,Z_2)$ with $Z_1 > Z_2$. The results for runs 9 and 10 do not appear to fit this trend, but the difference in average weight is small and the experimental error in the ratio is relatively large. Calculations[15] performed along the lines of Ref. 5 indicate consistently an increase in the slope of $n(W)$, with increasing ratio k_1/k_2 between heavier and lighter atoms. It might be possible to deduce the shape of $n(W)$ from the present experimental results with the target

TABLE II. Comparison between binary and ternary mixtures. In the last column, $A(Z_1,Z_2)_{norm}$ is the measured value of runs 7 and 9 in the cases of runs 8 and 10, respectively; Z_1 = Kr, Z_2 = Ne, and Z_3 = Ar. p is the total pressure.

Run	$Z_1/Z_2/Z_3$	$k_1/k_2/k_3$	p (bars)	$A(Z_1,Z_2)$	$\frac{A(Z_1,Z_2)}{A(Z_1,Z_2)_{norm}}$
7	Kr/Ne/ · · ·	69/31/ · · ·	16.2	2.83 ±0.16	1.00
8	Kr/Ne/Ar	21.7/9.8/68.5	51.1	2.54 ±0.14	0.90 ±0.02
9	Kr/Ne/ · · ·	36.8/63.2/ · · ·	16.5	2.60 ±0.11	1.00
10	Kr/Ne/Ar	11.5/19.8/68.7	51.0	2.82 ±0.11	1.08 ±0.05

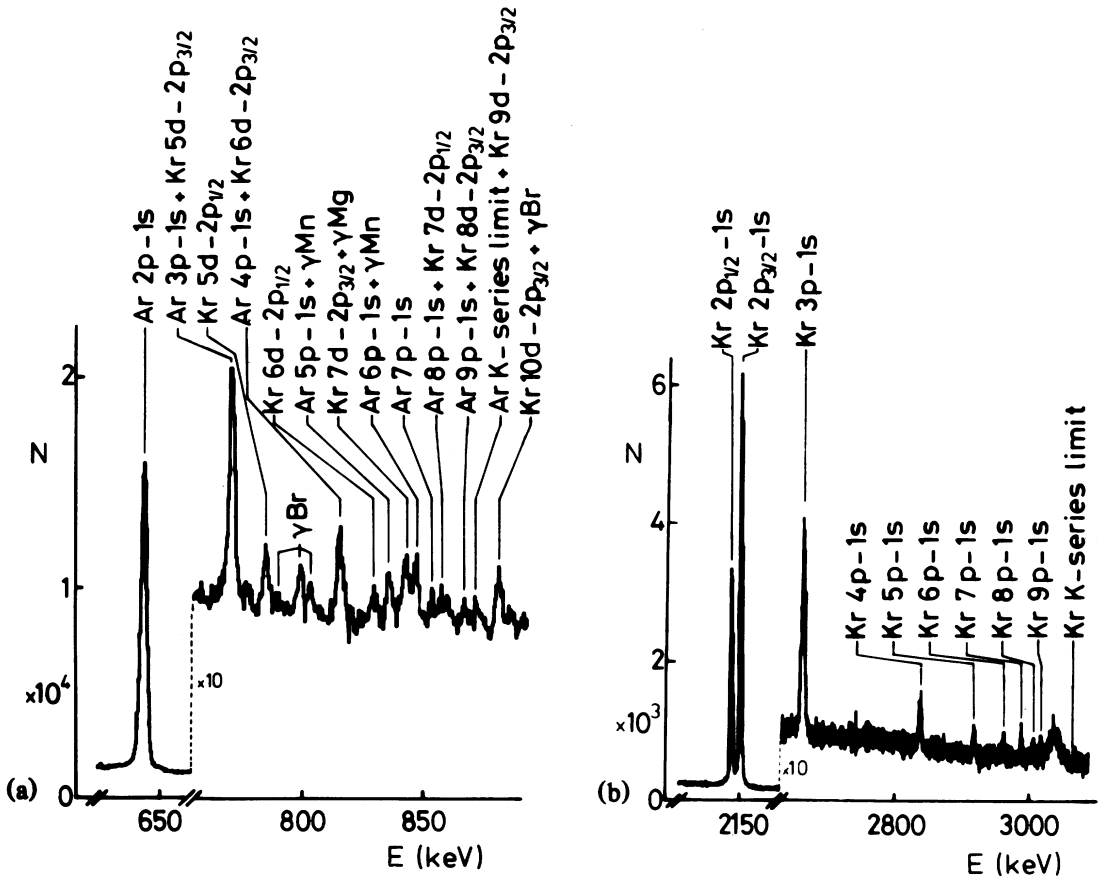

FIG. 1. Prompt spectrum from run 5 as measured with the Ge(Li) detector. Number of counts per channel plotted vs energy, one channel corresponding to 0.386 keV. (a) Ar Lyman series region; (b) Kr Lyman series region.

composition as parameter. Such a treatment will, however, need a detailed numerical investigation of the transport equation which has not yet been performed.

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[1]P. Vogel, P. K. Haff, V. Akylas, and A. Winther, Nucl. Phys. A254, 445 (1975).
[2]H. Daniel, Phys. Rev. Lett. 35, 1649 (1975).
[3]M. Leon, Phys. Rev. A 17, 2112 (1978).
[4]H. Daniel, Ann. Phys. (N.Y.) 129, 303 (1980).
[5]H. Daniel, Z. Phys. A 302, 195 (1981).
[6]J. D. Knight, C. J. Orth, M. E. Schillaci, R. A. Naumann, H. Daniel, K. Springer, and H. B. Knowles, Phys. Rev. A 13, 43 (1976).
[7]R. Bergmann, H. Daniel, T. von Egidy, F. J. Hartmann, J. J. Reidy, and W. Wilhelm, Phys. Rev. A 20, 633 (1979).
[8]R. A. Naumann, G. Schmidt, J. D. Knight, L. F. Mausner, C. J. Orth, and M. E. Schillaci, Phys. Rev. A 21, 639 (1980).
[9]R. L. Hutson, J. D. Knight, M. Leon, M. E. Schillaci, H. B. Knowles, and J. J. Reidy, Phys. Lett. 76A, 226 (1980).
[10]J. D. Knight, C. J. Orth, M. E. Schillaci, R. A. Naumann, F. J. Hartmann, J. J. Reidy, and H. Schneuwly, Phys. Lett. 79A, 377 (1980).
[11]J. P. Desclaux, At. Data Nucl. Data Tables 12, 311 (1973).
[12]R. A. Naumann and H. Daniel, Z. Phys. A 291, 33 (1979).
[13]*Handbook of Chemistry and Physics*, 60th ed. (Chemical Rubber Publishing Co. Press, West Palm Beach, Fla., 1979–80), p. D194.
[14]A. Eucken, *Lehrbuch der Chemischen Physik* (Akademische Verlagsgesellschaft, Leipzig, 1948), Vol. 2, Pt. 1, p. 233.
[15]P. Ehrhart, Ph.D. thesis (Technical University of Munich, 1982) (unpublished).