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Positron Lifetime Spectra in the Noble Gases*

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Positron lifetime spectra have been measured in helium, neon, argon, krypton, and xenon at pressures of a few atmospheres. The annihilation rates of the free positrons are found to be time-dependent. Physical reasons, based on the strong correlation between energy and age of a positron, are suggested for this time dependence. Three parameters describing the main features of the free-positron spectrum are separated from the data, for each gas, and tabulated.

POSITRON lifetime spectra have been measured in helium, neon, argon, krypton, and xenon at pressures of a few atmospheres.

It has long been supposed[1–6] that the lifetime spectrum of positrons released in a gas is a superposition of two exponentials:

$$I=I_1\lambda_1e^{-\lambda_1 t}+I_2\lambda_2e^{-\lambda_2 t}. \tag{1}$$

The first exponential describes the decay by annihilations of free positrons, the second the decay of triplet positronium. The free-positron annihilation rate is pressure-proportional. The pressure dependence of the positronium annihilation rate is given by

$$\lambda_2=\lambda_0+p\lambda_q, \tag{2}$$

where λ_0 is the natural annihilation rate of $1\,{}^3S$ positronium (0.7×10^7 sec^{-1}),[7] p is the gas pressure (strictly density) and λ_q is the quenching rate per unit pressure.

The lifetime spectra which have now been obtained (Fig. 1) contradict this simple picture.

The apparatus consisted essentially of a stainless steel vessel 10 in. in diameter containing the gas and a sodium-22 source. Two 5×5 in. cylinders of "Pilot B" scintillator mounted on 58 AVP photomultipliers detected the 1.3-MeV nuclear gamma ray and 0.51-MeV annihilation quanta, respectively. The outputs from the scintillation counters were fed to a specially designed time-amplitude converter of the "start-stop" type.[8] Resolution (full width at half-maximum of the prompt peak) under the experimental conditions was about 3 nsec.

The spectra of Fig. 1, as well as similar data at other pressures, consist of a prompt asymmetrical peak at $t=0$, followed by a gently sloping plateau and then an exponential decay. All these features show a strong pressure dependence. Aside from the prompt peaks these spectra are quite well described by 3 parameters:

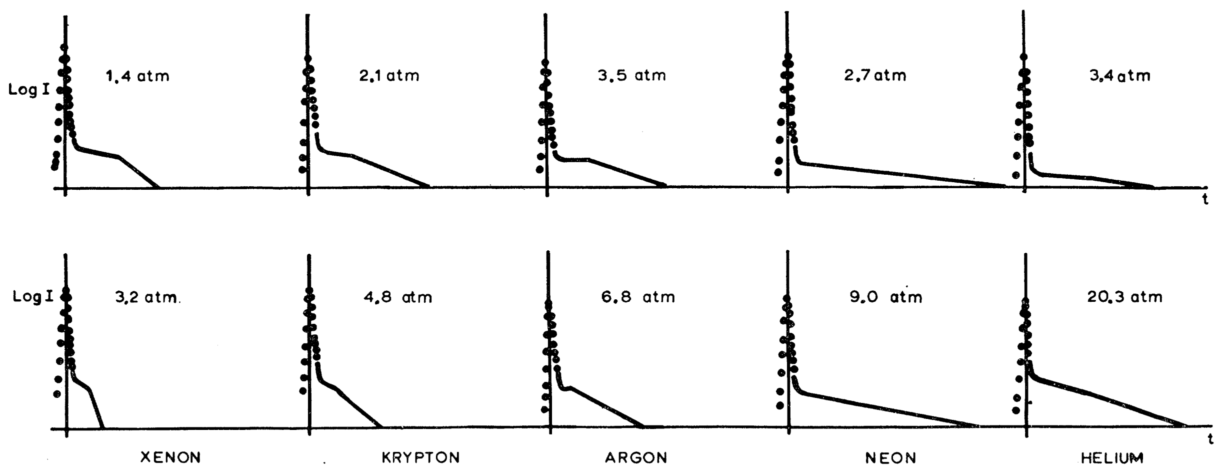

FIG. 1. Shapes of representative lifetime spectra of positrons in the noble gases.

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width of the plateau T, slope of the plateau λ, and the exponential decay rate Λ. $1/T$, Λ, λ were all found to be proportional to pressure. This fact together with the average lifetime of these positrons, compared with known positronium lifetimes in the noble gases,[4] demonstrates that we are observing free-positron lifetime spectra.

There was some evidence for a second exponential of smaller slope (the positronium component). But separation of two exponentials is notoriously difficult[5] and would have called for a longer time range than was available.

Interpretation of the data must depend on the strong correlation between lifetime and energy of the positron: annihilations within the first few nanosecond atmospheres occur while the positron is still making inelastic collisions; annihilations after a longer interval must be from positrons below the positronium threshold, and in general the longer the interval the lower the positron energy. This correlation, for the case of positrons in argon, has been discussed.[9] But the present uncertainty in the positron, atom collision cross section is the stumbling block. In principle, the lifetime spectrum can be transformed to a graph of positron annihilation rate versus energy. And it is precisely because low-energy positron-atom collision processes are not understood[10] that these measurements were made.

To a good approximation the spectra of Fig. 1 (aside from the prompt peaks) can be represented, on a semilog plot, by two intersecting straight lines: the plateau and the exponential decay.

The energy dependence of the free annihilation rate is expected to be as follows: at high energies (inelastic collisions region) the density of electrons in the path of a positron is the same as the average density of electrons in the material and the annihilation rate is the so-called[6] Dirac rate. At energies of a few electron volts, a positron is repelled by the atomic field so that the electron density and hence the annihilation rate are both reduced. Down towards thermal energies, electric polarization of the atom by the positron increases the effective electron density. If the polarization is sufficient, positron attachment will occur with rapid annihilation.

Thus, we associate the asymmetry in the prompt peak with annihilations at the Dirac rate, while the width T of the plateau measures the slowing-down time for the positron from some initial energy, below the positronium threshold, to the threshold for the process with characteristic rate Λ. This process can only be positron attachment. It can have the appearance of exponential decay if the threshold is below thermal energy and provided the relaxation rate for attaining thermal equilibrium is greater than the rate of absorption of free positrons by attachment, i.e., Λ.

The slope λ of the plateau is a measure of the annihilation rate at energies in the range positronium threshold to thermal. For He, Ne, Kr, and Xe, but particularly Kr and Xe for which the slope λ is rather constant, λ is this annihilation rate. Argon is anomalous in that the slope of the plateau is positive indicating an annihilation rate continuously increasing as the energy is reduced.

The plateau phenomenon has been observed in argon by Tao, Bell, and Green.[11] They find a plateau width

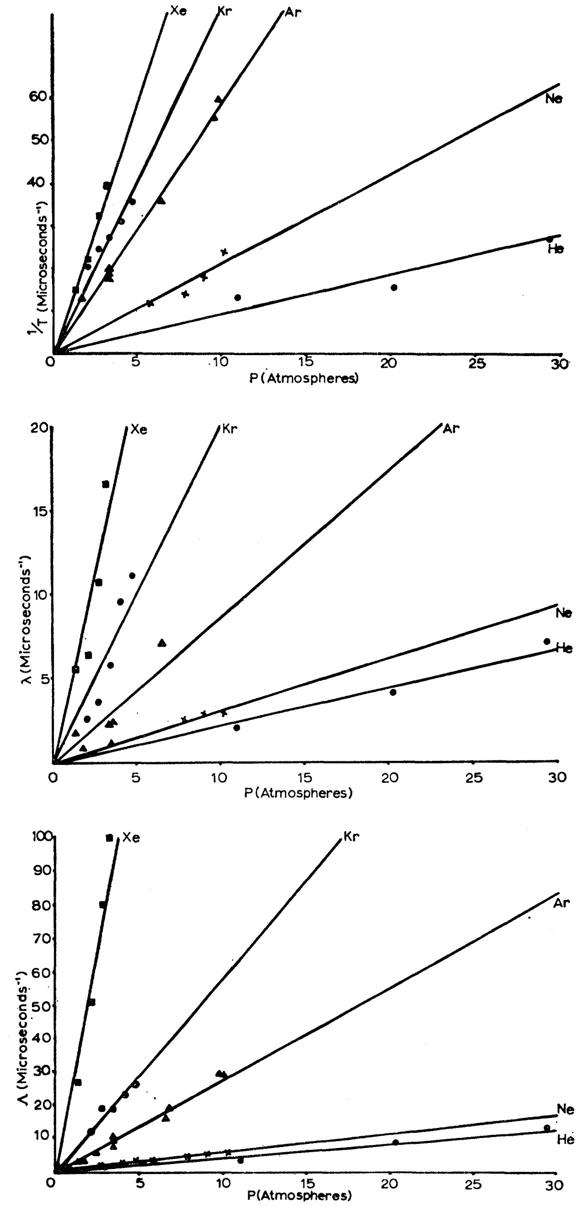

FIG. 2. Pressure dependence of $1/T$, λ, Λ for the noble gases.

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TABLE I. Comparison of measured rates with dirac rate.

	$(\mu\text{sec})^{-1}$		$(\text{atm})^{-1}$	
	λ_{Dirac}	λ	Λ	$1/T$
Xe	11	4.0_0	$26._3$	$11._6$
Kr	7.2	1.9_4	5.7_8	7.9_0
Ar	3.6	1.0_7	2.7_8	6.0_0
Ne	2.0	0.32_0	0.66_1	2.0_5
He	0.40	0.21_7	0.45_3	0.89_6

about 40% narrower, but also find it has a positive slope. Apparently, they found this positive slope somewhat unstable, presumably because of varying purity of the argon. The large scatter of the argon points on the λ graph of Fig. 2 also reflects this effect.

Tao *et al.* account for their results in terms of an annihilation rate increasing with time resulting from polarization of the atoms at low-energy collisions. However, this polarization alone is not sufficient to account for the sharp change of annihilation rate at the end of the plateau, particularly in krypton and xenon, and one must assume positron attachment.

The experimental results are collected in Table I. As already remarked the time-energy correlation is not one-to-one and so they cannot be interpreted directly in terms of cross sections. A full statistical treatment is needed, either by a diffusion-equation approach after Teutsch and Hughes[12] or the equivalent random-walk method. Theory must provide both collision cross sections and annihilation rates (neither of which can be obtained directly from the other) to give a complete description of the history of positrons in a gas.

It will now be possible to test such a description in detail by varying the environment of the positrons. In this way one confidently expects to reach understanding of the low-energy atomic collisions of particles of electronic mass.

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A New Dynamical Model for Meson States

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Reasons are advanced for considering the effect of inelastic coupling to the vector-vector state on the meson states occurring in pseudoscalar-pseudoscalar scattering. A model based on the angular-momentum properties of the box graph containing 2 vector mesons in the intermediate state is developed. In the dynamics of the model the "elementary" vector-meson octet disappears, and a vector-octet Regge trajectory is generated. A Pomeranchuk trajectory is generated in the singlet amplitude. The slopes of the trajectories are in quite reasonable agreement with experimental indications. The model predicts a $\rho\pi\pi$ coupling constant a factor of 2 or 3 above the experimental value and about the same as the value predicted by bootstrap models. The model shares with bootstrap models the feature that SU_3 symmetry is "predicted" as a consequence of dynamical self-consistency. The basic effect is expected to be important in more conventional dynamical schemes, and suggestions are made for further work.

I. INTRODUCTION

IN this note we propose a new dynamical model for the resonant states occurring in the scattering of two pseudoscalar mesons. We suggest that a hitherto unnoticed mechanism[1]—the inelastic coupling to the vector-vector state—is important to the generation of these resonances. The calculations are done in a simple dynamical scheme involving complex angular momentum. This is of interest in itself, but we expect the basic mechanism to be successful in more conventional dispersion-theoretic schemes, and suggestions are made for future calculations.

We distinguish between two types of dynamical models for particle states: Simple exchange models in which single particles in the crossed channels generate particle poles in the direct channel, and models in which the poles are generated as a consequence of coupling to inelastic states. Models of the first type for the meson system, based on the bootstrap idea,[2] enjoy considerable popularity. But both types of models are necessary to understand the baryon states, and we therefore consider models of the second type for the meson system.

Our work is partly motivated by the theoretical status of the $J^P=\frac{3}{2}^-$ resonances in meson-baryon scattering. In a model based on vector-meson exchange forces and reciprocal bootstrap[3] forces due to exchange

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