COMMENTS AND ADDENDA

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Nuclear Capture of Muons in Argon and Neon

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The total nuclear capture rates of muons by argon and neon have been measured. The experiment was performed by stopping negative muons in a target of ultrapure gaseous deuterium (at 6 atm pressure and 293 °K) separately contaminated by small amounts of argon and neon, and observing the differential time distribution of the decay electrons coming from muons stopped within the gaseous mixture. The results are $\lambda_{c,\mathrm{Ar}} = (1.20 \pm 0.08) \times 10^6$ sec^{-1} and $\lambda_{c,\mathrm{Ne}} = (0.30 \pm 0.02) \times 10^6$ sec^{-1}.

The total nuclear capture rates of muons by complex nuclei were measured in the past for a wide number of elements.[1] We report here a measurement of the nuclear capture rates of muons by argon—which had not been determined so far—and by neon, for which results are available[2,3] from experiments performed at the temperature of liquid hydrogen.

The measurements were performed at the 600-MeV CERN synchrocyclotron stopping negative muons in a target of ultrapure gaseous deuterium at room temperature, to which a small concentration of argon or neon was separately added. The capture rate $\lambda_{c,Y}$ (Y being in turn Ar or Ne) was determined by observing the time distribution dn_e/dt of the decay electrons coming from the muons stopping in the gaseous mixture, and by comparing it to the theoretical yield.

In these experimental conditions, dn_e/dt depends both on $\lambda_{c,Y}$ and on the rate of the muon transfer reaction,

$$\mu d + Y \to \mu Y + d \;, \qquad (1)$$

which the μd atoms initially formed in the target may also undergo. For this reason, the technique of observing dn_e/dt in a similar case was recently exploited to determine the rates of transfer processes like reaction (1) for the case Y = xenon,[4] for which the muon nuclear capture rate is expected to be much larger[1] than the muon decay rate λ_0. However, for elements such that $\lambda_{c,Y}$ has about the same order as λ_0—as one expects for argon and neon—dn_e/dt turns out to be particularly sensitive to the value of $\lambda_{c,Y}$, so that we have now followed this technique to determine $\lambda_{c,\mathrm{Ar}}$ and $\lambda_{c,\mathrm{Ne}}$.

We describe the method used with regard to $\lambda_{c,\mathrm{Ar}}$ only, since $\lambda_{c,\mathrm{Ne}}$ was obtained quite by the same procedure. Negative muons from the 600-MeV synchrocyclotron were slowed down in the gaseous target (containing 6 atm of pure deuterium at 293 °K, contaminated by an argon concentration $c_{\mathrm{Ar}} = 4.9 \times 10^{-4}$). The injected argon was 99.9% pure. The 125-MeV/c muon beam had an intensity of 15 000 particles sec^{-1} over an area of 10×10 cm^2. The rate of muons stopping within the gas was about 50 sec^{-1}.

Under these conditions, the following statements hold: (i) The nuclear capture rate of muons by deuterons in the primary μd atoms formed within the target is much smaller[5] than λ_0. The formation of $d\mu d$ molecular ions[6] is also negligible due to the reduced density of the gaseous target.

(ii) Since the absolute rate of muon transfer from μd atoms to other elements is quite high,[7] process (1) occurs in the target at an effective rate which is made of the same order of λ_0 by the chosen value of

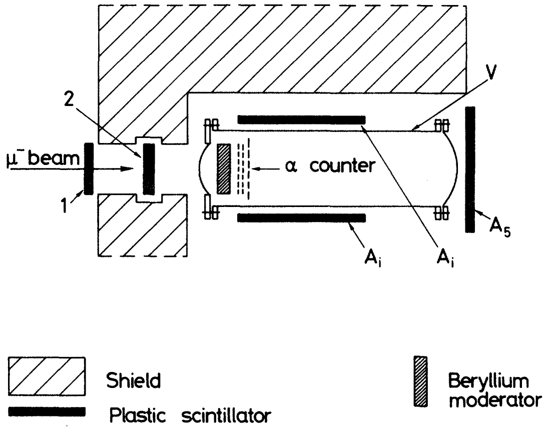

FIG. 1. Simplified diagram of the apparatus. V is a stainless-steel vessel; 1, 2, A_i are plastic scintillator detectors.

c_{Ar}. This reaction produces an excited $(\mu Ar)^*$ muonic atom, which promptly decays to the 1S level emitting x rays[8] and one or more Auger electrons. The muon in the μAr system can finally decay or undergo nuclear capture at a rate $\lambda_{c,Ar}$.

(iii) The differential time distribution dn_e/dt of the decay electrons coming from muons stopped within the gaseous mixture is given by

$$\frac{dn_e}{dt}=A\frac{\lambda_0}{\lambda_{c,Ar}-\gamma c_{Ar}\lambda_{\mu d,Ar}}\times\{\lambda_{c,Ar}\exp[-(\lambda_0+\gamma c_{Ar}\lambda_{\mu d,Ar})]t-\gamma c_{Ar}\lambda_{\mu d,Ar}\exp[-(\lambda_0+\lambda_{c,Ar})]t\}\ , \quad (2)$$

where A is a constant, γ is the ratio between the density of deuterium and the density of liquid hydrogen, c_{Ar} is defined as the ratio between the partial pressure of argon and the total pressure of the gaseous mixture, and $\lambda_{\mu d,Ar}$ is the rate at which reaction (1) takes place for Y= Ar when the density of argon molecules is equal to the density of liquid hydrogen (2.11×10^{22} molecules cm^{-3}).

As was previously said, it is seen from Eq. (2) that dn_e/dt is sensitive to the value of $\lambda_{c,Ar}$ only if this rate is comparable to λ_0 in size. On the other hand, owing to the chosen value for c_{Ar}, the observed time distribution will have a decay time long enough to eliminate by a proper time cut the short-lived component due to those muons stopped in the iron walls of the container. (The time distribution of the decay electrons coming from muons stopping in iron has a mean lifetime of about 200 nsec.[1])

The main features of the apparatus—which was described in Ref. 4—are shown in Fig. 1. Counters 1, 2, and A_i's are plastic scintillators, and counter α is a wire-grid proportional counter, working with the gaseous mixture itself as a filling gas.

A negative muon stopping within the gaseous target V is defined by an anticoincidence signal STOP $=(1, 2, \alpha, -\sum A_i)$ [here (–) means "not"]. The STOP signal opens a gate 10 μsec long, during which the decay electrons are accepted, and their delay with respect to the STOP signal is measured.

The experimental time distribution of the muon decay electrons detected by the plastic scintillators A_1, A_2, A_3, and A_4 in the measurement referring to argon is shown in Fig. 2. Background counts

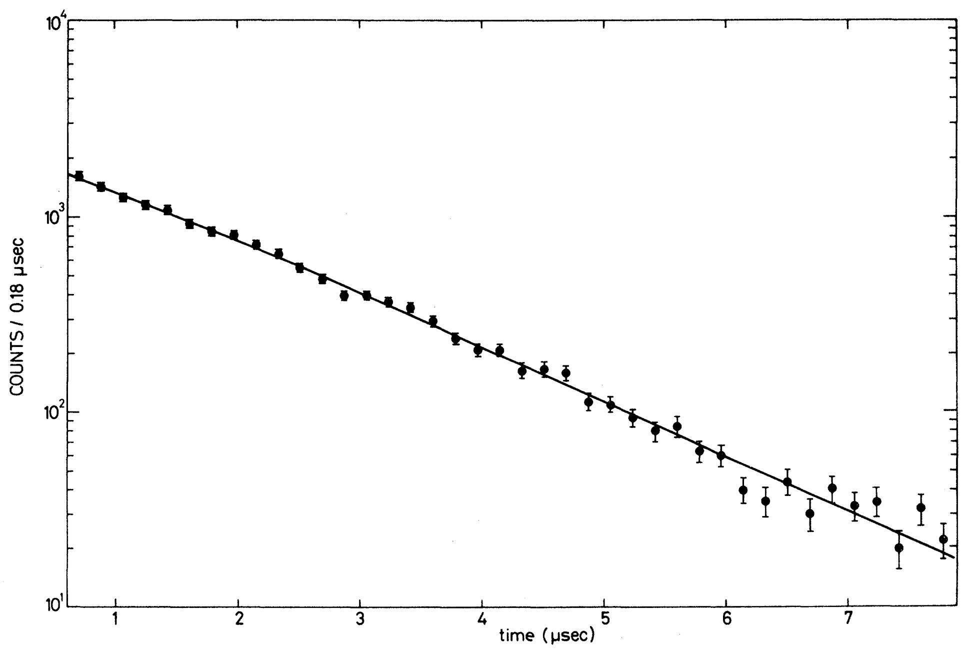

FIG. 2. Differential time distribution dn_e/dt obtained for the measurement of the nuclear capture rate of muons by argon. The full line represents the best fit to the experimental points. Number of points: 40; $\chi^2=30$. No. of degrees of freedom = 2.

TABLE I. Comparison between the results of the present measurement and those of previous experimental and theoretical work.

Element	Nuclear capture rates (10^6 sec^{-1}) Experimental results	Theoretical values
Ar	1.20 ± 0.08[a]	not available
Ne	0.167 ± 0.030[b]	
	0.204 ± 0.010[c]	0.27[d]
	0.30 ± 0.02[a]	0.28[e]

[a]Present experiment.
[b]See Ref. 2.
[c]See Ref. 3.
[d]Calculated value obtained on the basis of the Primakoff formula (see Ref. 3).
[e]See Ref. 10. This value was obtained assuming an average neutrino momentum $\bar{\nu} = 0.75$ (in muon masses) and a deformation and Nilsson configuration of the nucleus similar to those calculated by Paul (see Ref. 13) for ^{19}F.

have been subtracted in the figure, and a lower time cut of 0.6 μsec was performed on the experimental points. These data were fitted by Eq. (2), leaving $\lambda_{c,\,\mathrm{Ar}}$ and $\lambda_{\mu d,\,\mathrm{Ar}}$ as free parameters. The best fit obtained is represented by the full line in the figure, and yields

$$\lambda_{c,\,\mathrm{Ar}} = (1.20 \pm 0.08) \times 10^6 \ \mathrm{sec}^{-1}. \qquad (3)$$

As to $\lambda_{\mu d,\,\mathrm{Ar}}$, the best fit gives a value which is in good agreement with the result by Placci *et al.*[7]

The measurement of $\lambda_{c,\,\mathrm{Ne}}$ was carried out filling the gaseous target with 6 atm of ultrapure deuterium, to which a neon concentration $c_{\mathrm{Ne}} = 1.4 \times 10^{-3}$ had been added. The time distribution of the muon decay electrons observed in this case is given in Fig. 3 after background subtraction. We obtain in this way

$$\lambda_{c,\,\mathrm{Ne}} = (0.30 \pm 0.02) \times 10^6 \ \mathrm{sec}^{-1}. \qquad (4)$$

The present results are listed in Table I, where the value obtained for $\lambda_{c,\,\mathrm{Ne}}$ is also compared to the preceding experimental data by Conforto *et al.*[2] and by Rosen *et al.*[3] It is seen that the present value for $\lambda_{c,\,\mathrm{Ne}}$ is larger than the ones obtained by these authors. On the other hand, it turns out to be in better agreement with the theoretical predictions one gets on the basis of the Primakoff formula[9] and from the calculation by Silbar.[10] This author obtained the value shown in Table I in the framework of the unified Nilsson model,[11] starting from the usual universal-Fermi-interaction and conserved-vector-current assumptions[12] on the vector (g_V), axial (g_A), and pseudoscalar (g_P) couplings, with $g_P = 8g_A$.

As a final remark on the experimental results on $\lambda_{c,\,\mathrm{Ne}}$, we notice here that the previous measurements of this rate were performed using a liquid-hydrogen target in which small amounts of neon were dissolved. However, we believe that, when this type of technique is followed, working with a gaseous target enables one to more precisely control the actual contamination of neon.

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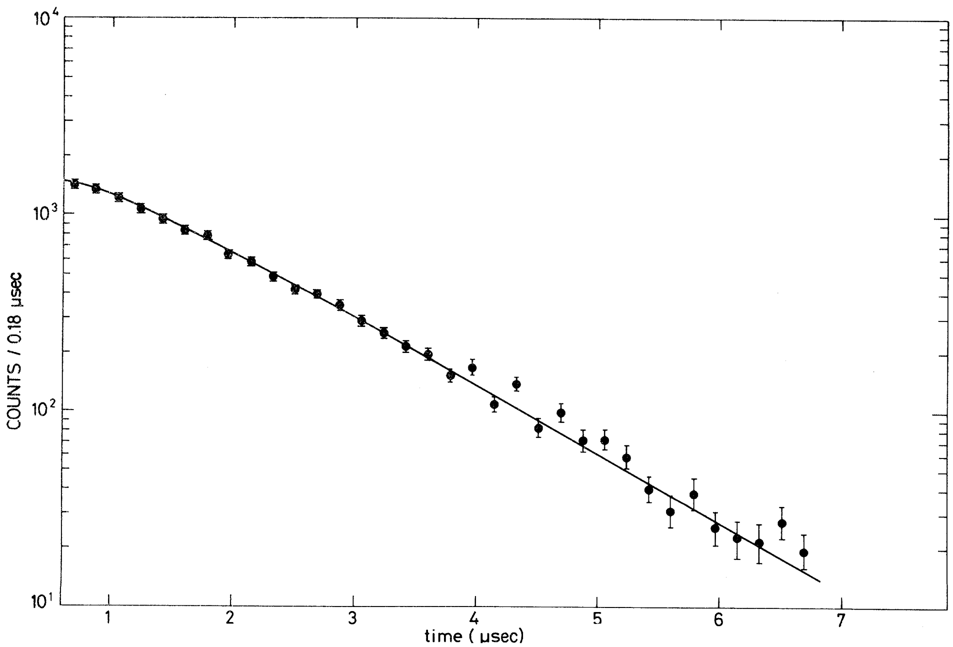

FIG. 3. Differential time distribution dn_e/dt obtained for the measurement of the nuclear capture rate of muons by neon. The full line is the best fit to the experimental points. Number of points: 34; $\chi^2 = 38$. No. of degrees of freedom = 2.

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Electron Scattering with and without Vibrational Excitation. VIII. Comment on a Theory of Small-Energy-Transfer Collisions Dominated by Long-Range Forces

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Two methods [D. G. Truhlar and J. K. Rice, J. Chem. Phys. 52, 4480 (1970) and B. Ritchie, Phys. Rev. A 6, 1456 (1972)] for calculating cross sections for vibrational excitation of molecules by electron impact are compared. The former method is shown to have a greater range of applicability. Cross sections computed by the two methods differ by about a factor of 2 for excitation to the first vibrationally excited level of H_2. The neglect of the short-range potential in Ritchie's method is shown to be an important source of error in that method.

Recently, Ritchie[1] has proposed a quantum-mechanical theory for cross sections for vibrational excitation in collisions dominated by long-range central potentials. Previously, a theory applicable to such collisions had been proposed by the author and Rice.[2,3] It is of some interest to compare these theories. The latter theory is the polarized Born approximation and it includes not only the spherically symmetric part of the long-range potential but also the short-range potential and the asymmetry of the potential. The polarized Born approximation is also more general in that it does not require the assumption of small energy transfer. Ritchie's calculation evaluates the eigenphase shifts in the high-energy limit. The high-energy approximation is similar to, but not identical to, the plane-wave approximation in the polarized Born calculations; the relationship of the two approximations has been discussed elsewhere.[4,5] In the present article we consider vibrational excitation of N_2 and H_2 by electron impact.

First we consider excitation of the $v'=1$ vibration. The data needed for the calculations by Ritchie's method are R_e (the equilibrium internuclear distance), ϵ (the vibrational excitation energy), α_{10}, and $\alpha \equiv \frac{1}{2}(\alpha_{11}-\alpha_{00})$, where

$$\alpha_{v'v} = \int \psi^*_{v'}(R)\, \alpha(R)\, \psi_0(R)\, dR \qquad (1)$$

and $\psi_{v'}(R)$ is a vibrational wave function and $\alpha(R)$ is the static dipole polarizability as a function of internuclear distance. These data were computed for H_2 by the method of Paper I and are given[6] in Table I as data set 1 (DS1). These data are essentially the same as Ritchie's data set (RDS), in which $\alpha_{vv'}$ is taken from Henry's calculations.[7]

For N_2, Ritchie used H_2 matrix elements scaled to account for the different polarizability of N_2 at R_e. This yields the data labeled RDS in Table I. A more accurate data set (ADS) was determined by the following procedure. Assume

$$\alpha(R) \cong \alpha(R_e) + \left(\frac{d\alpha}{dR}\right)\bigg|_{R=R_e} x\,, \qquad (2)$$

where $x = R - R_e$. Define

$$x_{v'v} = \int \psi^*_{v'}(R)\,(R-R_e)\,\psi_v(R)\, dR\,. \qquad (3)$$

These matrix elements were computed by an accurate numerical method[8] using vibrational wave functions corresponding to the accurate N_2 potential function of Levine.[9] The results are $x_{00}=7.192\times10^{-3}$, $x_{01}=6.058\times10^{-2}$, and $x_{11}=2.174\times10^{-2}$. From $d\alpha/dR\,|_{R=R_e} \cong 5.71$[10,11] and x_{01}, we obtain α_{01}. From