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Observation of the metastable negative beryllium ion, Be^- ($^4P^e$)

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The existence of the theoretically predicted $2s2p^{2}\,^4P^e$ metastable Be^- ion has been confirmed by experiment. The autodetachment decay rates at several decay times after formation show the presence of more than one substate, with the lifetime of the longest component exceeding 100 μs.

The existence and properties of metastable excited negative ions with lifetimes $\geq 10^{-6}$ s have attracted both theoretical and experimental interest for some time. Until recently, only He^- had been firmly established and studied, while H_2^-, H_3^-, N^-, N_2^-, Be^-, and Mg^- had been only inconclusively observed or predicted by theory. Experimental progress was inhibited because the spin configurations that render these ions metastable against autodetachment also prevent their direct formation in conventional ion sources. This difficulty can be overcome by a two-step electron capture method (starting with a positive ion beam) which we have begun to exploit in studies of He^- (Refs. 1 and 2) and in a search for various other members of this family. This search has thus far shown that H_2^- and H_3^- probably do not exist,[3] but has discovered the unpredicted He_2^- metastable,[4] which has now been confirmed theoretically.[5]

Although the electron affinity of $2s^{2}\,^1S$ ground state Be is negative, *ab initio* configuration interaction (CI) calculations[6] have found that a "core-excited" $2s2p^{2}\,^4P^e$ state of Be^- is metastable and bound below Be ($2s2p\,^3P$) by 0.24 eV (Fig. 1). It thus lies about 2.5 eV above Be ($2s^{2}\,^1S$). The first observation of Be^- was reported by Bethge, Heinecke, and Baumann,[7] who used direct radial extraction of negative ions from a metal vapor plasma in a Penning ion source. However, neither strong proof of its existence nor confirmation of the metastability were established, although it was later reported again by the same group.[8] In this Rapid Communication, we report the observation of Be^- produced from Be^+ by two-step electron capture, and the first confirmation of its predicted metastability, measurements of its decay rate, and the observation of its photodetachment.

The main part of the experimental arrangement is shown schematically in Fig. 2. Be^+ ions were produced in a Colutron ion source by first introducing a small piece of Be metal directly into the ion source, and then admitting CCl_4 vapor to support the discharge of the ion source, as well as to react chemically with the Be. Apparently, the vapor pressure of chemically formed $BeCl_2$ is sufficiently high to permit easy formation of Be^+ by gas-phase collisions with the primary electrons in the discharge. The accelerated (to 3.5 keV in this work) and momentum-analyzed Be^+ beam was then directed through a Cs vapor cell to form the negative ions. In this two-step capture process, presumably the first step is mainly

$$Be^+ + Cs \rightarrow Be(2^3P) + Cs^+ \quad , \tag{1}$$

although production of $Be(2^3P)$ by the radiative decay of higher triplets is possible. The second step is almost certainly

$$Be(2^3P) + Cs \rightarrow Be^-(^4P^e) + Cs^+ \quad . \tag{2}$$

Although reaction (1) is 2.7 eV exothermic, and capture to Be ($2s2p\,^1P$), which is closer to resonance (see Fig. 1) with $\Delta E \sim 0.15$ eV, probably dominates the overall charge transfer, we easily produced enough Be^- for these initial studies using Cs, and no attempt was made to examine production in other alkali vapors. In any case, reaction (2) is the production limiting step, and here Cs is probably better than the lighter alkalis.

After traversing the Cs vapor cell, the +, 0, and − charged beam components were separated by an electrostatic quadrupole deflector Q1, which serves as a crude energy analyzer as well as a charge separator. After passing two 1.4-mm (horizontal) × 2.2-mm (vertical) apertures which define the photon-ion beam interaction region, the negative component with the selected energy entered the second de-

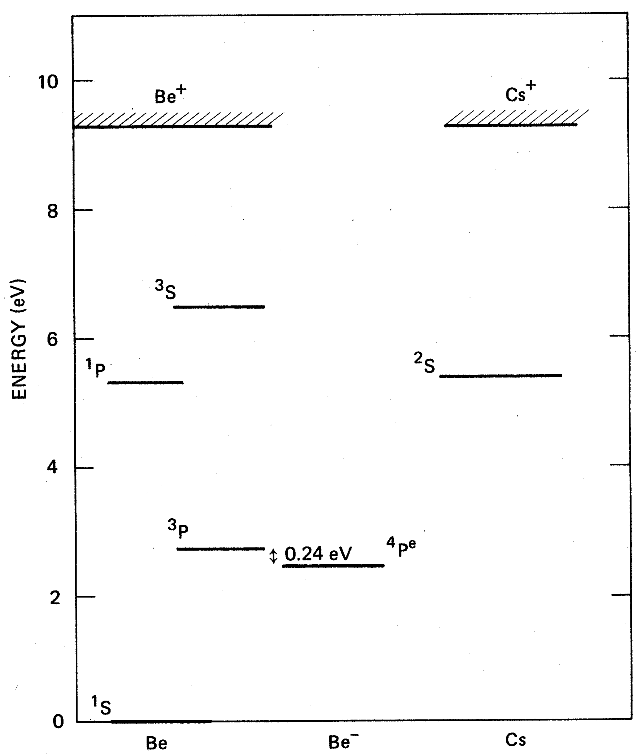

FIG. 1. Electronic levels.

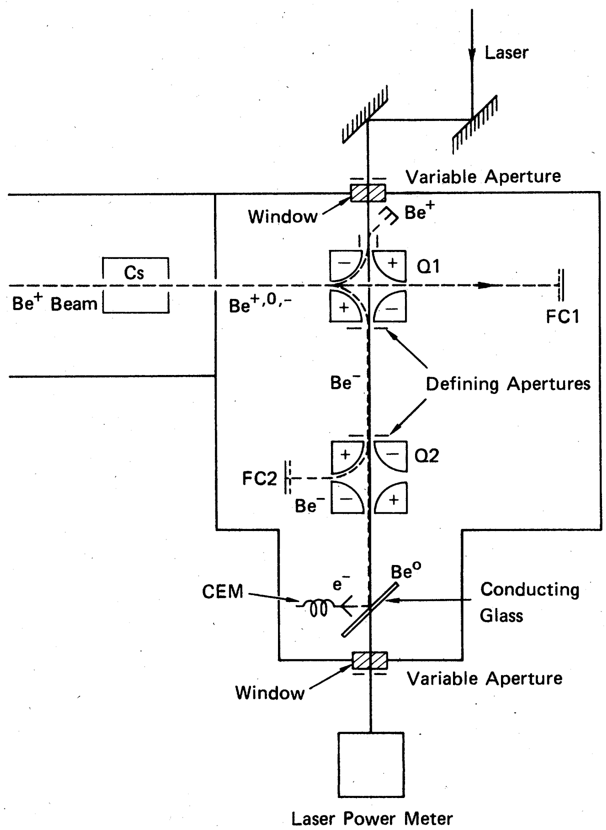

FIG. 2. Schematic diagram of the main experimental arrangement. The details of the laser and the shields blocking the secondary particles are not shown.

flector Q2, where it was directed to a Faraday cup FC2 for measuring current. The fast neutrals formed in the field free drift region between Q1 and Q2 by autodetachment, collisional detachment, or photodetachment passed undeflected to the conducting surface (indium oxide coated) of a glass plate, from which secondary electrons were drawn to the positively biased cone of a channel electron multiplier (CEM) for counting. The conducting glass plate allows detection of the fast neutrals while simultaneously monitoring a laser beam placed coaxially with the ion beam during photodetachment measurements.

To estimate the Be^- autodetachment lifetime and to see whether there is evidence of more than one state, we measured the effective decay rates at various ion velocities to vary the Be^- flight time between creation and observation. These decay rates are defined by

$$\Gamma_{\text{eff}} = v i_a / l i^- ,$$

where v is the ion velocity, l the Q1-Q2 distance, i_a the current of autodetached neutrals counted by the CEM, and i^- the negative ion current measured by FC2. To separate the autodetached component of the neutrals from the collisionally produced neutrals, the total decay count rate was measured as a function of the background pressure in the analysis chamber by varying the opening of the valve to the diffusion pump (Fig. 3). The zero calibration of the ion gauge was checked by observing collisionally detached neutrals from Li^-, which does not autodetach. As shown in Fig. 3, the collisionally detached neutral current was negligible compared to the autodetached neutrals. The autodetachment rates measured at several beam energies between 3 and 5 keV were not constant, but decreased monotonically from 1×10^5 to 5.9×10^4 s^{-1} as the flight time of the ion from the Cs cell to Q1 varied from 1.8×10^{-6} to 2.4×10^{-6} s. This indicates the presence of some components with lifetimes about 10^{-4} s, and others with lifetimes about 10^{-5} s, as is the case for $He^-(^4P^0)$. If we assume that the quantum state of Be^- is $^4P^e$, then (as with He^-) presumably the $J=\frac{5}{2}$ state would have the longest lifetime (~ 100 μs), and the $J=\frac{3}{2}$ and $\frac{1}{2}$ states the shorter lifetimes (~ 10 μs) because of their spin-orbit coupling to autodetaching $Be^-(^2P^e)$ states.

To further test the properties of this ion, photodetachment was performed by chopping the laser beam and accumulating the counts from the neutral detector corresponding to laser on and off in the two channels of a PAR model 1112 processor. Selected single lines of a Kr^+ laser have been used to get the photon energies from 1.65 to 2.34 eV. Considerable care was taken to optimize the overlap of the beams, laser, and ions as they both filled the beam defining apertures in Q1 and Q2, we assume the beam overlap to be approximate unity. In this case, the photodetachment cross

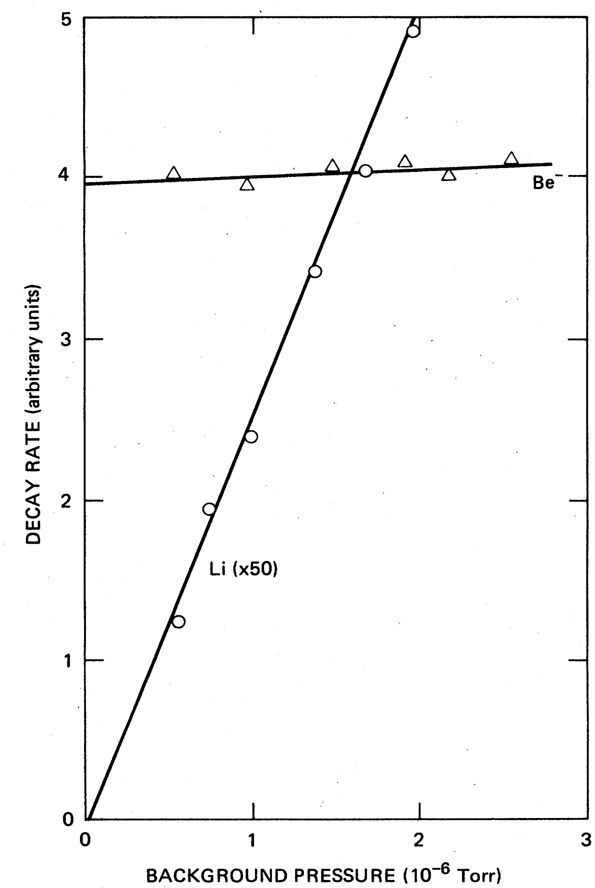

FIG. 3. Counting rates of fast neutrals produced from Be^- and Li^- autodetachment and collisions between Q1 and Q2 vs background pressure in the analysis chamber.

section is given by

$$\sigma = Sav/li^{-}i_{p}D \quad ,$$

where D is the detection efficiency of the Be neutrals, S the photodetachment signal/s, a the area of the defining apertures, v the velocity of Be^{-} ion, i^{-} Be^{-} current, i_p the equivalent photon current, and l the length of the interaction region. The detection efficiency D depends on the secondary electron coefficient of the 3.5-keV Be neutrals that impact on the indium oxide coating of the glass plate. The maximum value of $D=1$, which we have arbitrarily used to estimate the cross sections shown in Fig. 4; thus, they represent upper limits. However, in recent experiments on Li^{-} photodetachment,[9] we measured $D=0.9$ for 3-keV Li atoms on the same surface and the D for 3.5-keV Be should not be much lower. In any case we estimate the uncertainties on the data in Fig. 4 to be $\sim 50\%$.

The photon energy region covered in this work occupies the $Be(2^3P)+\epsilon(s,d)$ continuum, and for energies above the d-wave maximum it is expected to decrease monotonically until the $3^3S+\epsilon p$ threshold is reached, except for possible perturbations due to spin-orbit coupling to the $3^1P+\epsilon s$ channel at or near its threshold at $h\nu = \sim 2.8$ eV. Thus, the monotonic decrease shown here indicates that the d-weak peak lies toward lower energies. Noting that the calculated cross section for $s+d$ wave from He^{-} peaks at only 0.2 eV above threshold,[10] it is not surprising that these data appear to be in the high energy tail. A summed oscillator strength ~ 0.07 is included in the region of the present data. We are planning much more work on Be^{-} photodetachment, which should reveal the locations of various resonant states of Be^{-} as well as provide more accurate cross sections.

In summary, we have confirmed the existence of the metastable Be^{-}, performed preliminary measurements of its decay rates, and measured photodetachment cross sections in the photon energy range 1.65–2.34 eV. Be^{-} is, thus, the second atomic negative ion whose decay has been confirmed, and should become a subject of fruitful experimental and theoretical studies. This observation also strengthens the possibility of the existence of metastable Mg^{-}, Ca^{-}, Sr^{-}, and Ba^{-} ions.

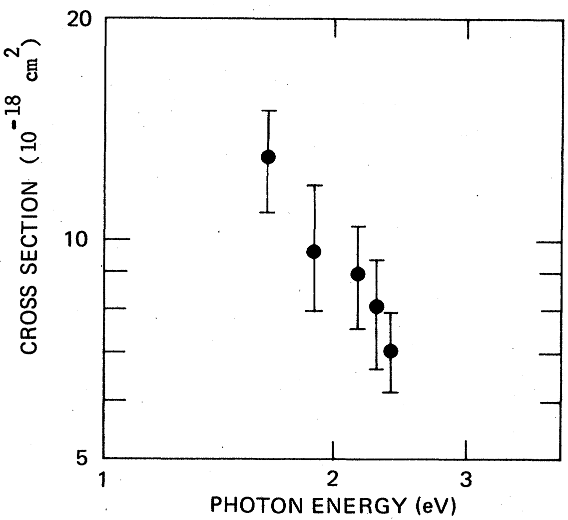

FIG. 4. Photodetachment cross sections.

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[1]R. V. Hodges, M. J. Coggiola, and J. R. Peterson, Phys. Rev. A **23**, 59 (1981).
[2]J. R. Peterson, M. J. Coggiola, and Y. K. Bae, Phys. Rev. Lett. **50**, 664 (1983).
[3]Y. K. Bae, M. J. Cogiola, and J. R. Peterson, Phys. Rev. A **29**, 2888 (1984).
[4]Y. K. Bae, M. J. Coggiola, and J. R. Peterson, Phys. Rev. Lett. **52**, 747 (1984).
[5]H. H. Michels, Phys. Rev. Lett. **52**, 1413 (1984).
[6]A. W. Weiss, Phys. Rev. **166**, 70 (1968); C. F. Bunge, M. Galán, R. Jáuregui, and A. V. Bunge, Nucl. Instrum. Methods **202**, 299 (1982).
[7]K. Bethge, E. Heinecke, and H. Baumann, Phys. Lett. **23**, 542 (1966).
[8]H. J. Kaiser, E. Heinecke, H. Baumann, and K. Bethge, Z. Phys. **243**, 46 (1971).
[9]Y. K. Bae and J. R. Peterson (unpublished).
[10]A. V. Hazi and K. Reed, Phys. Rev. A **24**, 2269 (1981).