Cross section for the photodetachment of Be^-

D. J. Pegg,* C. Y. Tang, and J. R. Wood
Department of Physics, University of Tennessee, Knoxville, Tennessee 37996

J. Dellwo and G. D. Alton
Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831
(Received 18 July 1994)

The cross section for single-photon detachment of an electron from the metastable Be^- ion has been measured at a photon energy of 2.076 eV to be 31±3 Mb. The method of laser photodetached electron spectroscopy was used in the measurement and the asymmetry parameter that characterizes the angular distribution of the detached photoelectrons was also measured to be $\beta=0.49\pm0.02$ at the same energy.

PACS number(s): 32.80.Fb

I. INTRODUCTION

We report on a measurement of the single-photon detachment cross section for the Be^- ion at a photon energy of 2.076 eV. At this energy, the photodetachment process proceeds via the ^3P $\varepsilon s,d$ final-state channels, i.e., $h\nu+Be^-(2\,^4P)\rightarrow Be(2\,^3P)+e^-(\varepsilon s,d)$. The asymmetry parameter β, which characterizes the angular distribution of the ejected photoelectrons, was also determined at the same energy.

The Be^- ion was apparently first observed by Bethge, Heinicke, and Baumann [1] in a mass spectrum of ions extracted from a negative-ion source. A theoretical investigation of this ion was subsequently made by Weiss [2]. It was found that Be^- belongs to an interesting class of negative ions that are unstable, yet long lived, as a consequence of being metastable against Coulomb autodetachment. The ion eventually autodetaches via the weaker magnetic interactions. The metastable Be^- is formed in the $1s^22s2p^2\,^4P$ state when an electron is attached to the Be atom in the metastable $1s^22s2p\,^3P$ state. The most accurate determinations of the binding energy of the $2\,^4P$ state to date are the calculated value of 276.1±6.5 meV by Bunge [3] and the measured value of 261±10 meV by Tang *et al.* [4]. There exists a differential metastability among the fine-structure levels of the metastable ^4P state due to the varying strengths of their couplings to the continuum. The first measurement of the level lifetimes was made by Bae and Peterson [5]. Recently, accurate lifetimes were reported by Balling *et al.* [6]. Interestingly, the $J=\frac{3}{2}$ level lives about 180 times longer than the $J=\frac{1}{2}$ and $\frac{5}{2}$ levels. There has been one previous measurement of the Be^- photodetachment cross section [5] but no calculations of this quantity exist at present. There have been no previous investigations, either experimental or theoretical, of the angular distribution of detached photoelectrons prior to the present work.

II. EXPERIMENTAL TECHNIQUE

A crossed-beam apparatus was used in the measurement. A schematic of the apparatus is shown in Fig. 1. A beam of Be^- ions was produced by charge exchange (sequential double electron capture) when a beam of Be^+ ions was passed through a Li vapor cell placed approximately 1 m upstream of the photon-ion interaction region. The trajectory of the negative-ion beam was defined by two apertures of diameters 1.5 and 2.0 mm separated by 85 mm. Between the apertures the ion beam was crossed perpendicularly by a beam of linearly-polarized photons from a flashlamp-pumped dye laser. The interaction region was situated approximately 15 mm upstream of the entrance aperture of a spherical-sector electrostatic electron spectrometer. Electrons ejected from the fast-moving ions, in the direction of motion of the ion beam, were collected and energy analyzed to produce the spectra. The spectral peaks were fitted to Gaussian functions to determine the photoelectron yields. The angle dependence of the yield was determined by rotating the polarization vector of the laser beam while keeping the collection fixed in the forward direction. This was accomplished by the use of a double Fresnel rhomb. The photoelectron signal was normalized to account for changes in both the ion and laser beam intensities. A background of electrons arose from collisional detachment of the ions due to interactions with the residual gas particles and the beam-defining apertures. The signal-to-background ratio was enhanced by employing a gated detection scheme based on the time structure of the laser pulses, i.e., the electron detector was gated on and off in coincidence with the presence or absence of laser radiation.

Photodetachment cross sections are determined, in the case of interacting beams, by measuring the yield, Y, of product particles (photoelectrons or residual atoms) for known values of the ion-beam density, ρ, and photon flux, ϕ, i.e., $\sigma=G(Y/\rho\phi)$. The quantity G incorporates the

*Also with the Physics Division, Oak Ridge National Laboratory.

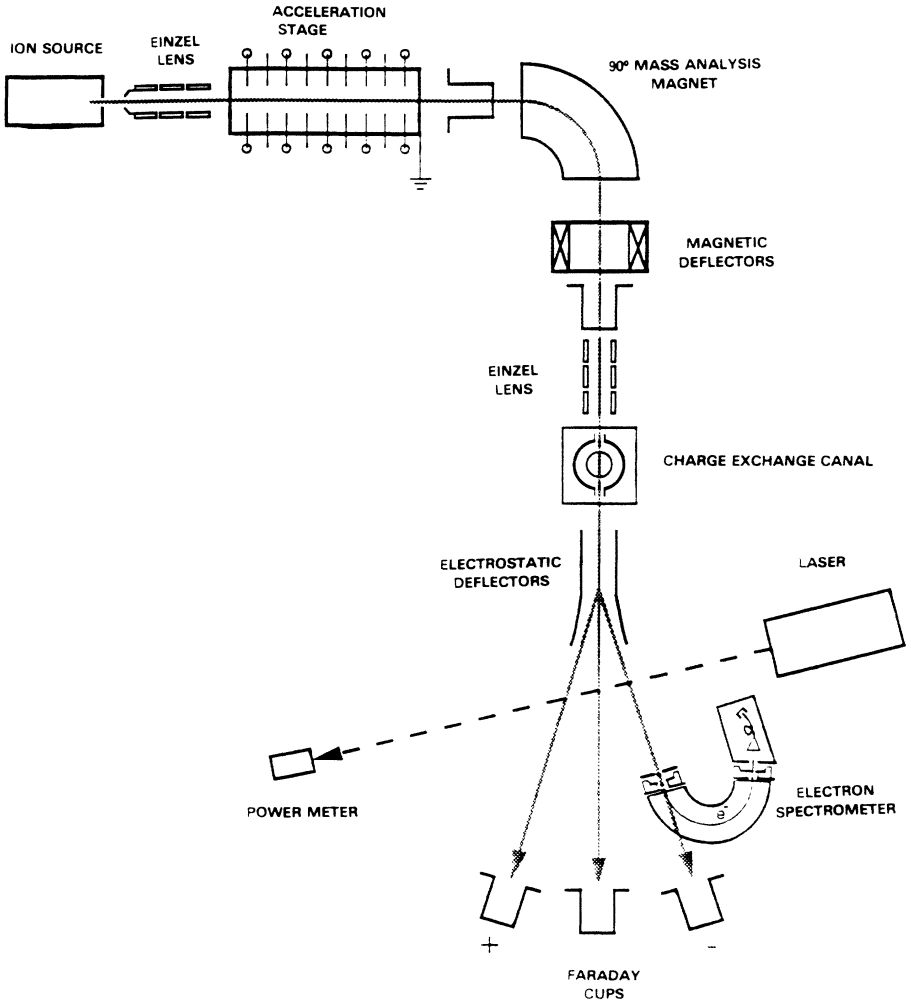

FIG. 1. A schematic of the crossed-beam apparatus used to determine photodetachment cross sections via the ratio method and photoelectron angular distributions.

efficiency for collection and detection of the product particles as well as the spatial and temporal overlap of the laser and ion beams. In the case of photoelectron detection, an additional measurement of the angular distribution of the detached electrons is required to convert the angle-differential measurement into an integral one. In absolute cross-section measurements the accuracy is ultimately limited by the difficulty of determining the quantity G. This problem may be circumvented by using a ratio method in which the cross section of the species of interest is measured relative to that of a reference species [7]. The ratio is then normalized to the known cross section of the reference species, in this case either Li^- or D^-. The Be^- beam and the chosen reference beam were passed sequentially through the laser field in the same manner. Tight collimation was required to keep the overlap of the interacting beams essentially unaltered during the relative measurement. Under this condition the yield ratio becomes independent of the beam overlap. Corrections to the measured yield ratio are applied to account for quantities that differ for the two species such as ion-beam intensities and velocities, photoelectron angular distributions, and kinematically-modified emission solid angles. The dependence of the ratio on the collection and detection efficiency for electrons detached from the two beams was eliminated in the present experiment by choosing the energies of the Be^- ion beam and the reference beam in such a way that kinematics shifted the energies of the groups of detached electrons to the same value in the laboratory frame.

III. RESULTS

In an angular distribution measurement, the yield of photoelectron is measured as a function of the angle, θ, between the collection direction and the direction of the polarization vector of the laser beam. For linearly-polarized radiation in the electric-dipole approximation, the photoelectron angular distribution should take the form $f(\theta)=1+\beta P_2(\cos\theta)$, where β, the asymmetry parameter, is a measure of the deviation from isotropy and $P_2(\cos\theta)$ represents a second-order Legendre polynomial. It is assumed that prior to photoabsorption the ions are unpolarized. Justification for this assumption is based on the fact that an aligned orbital angular-momentum vector would be coupled to a randomly aligned spin vector for many spin-orbit precession periods during the transit time (2 μ sec) of the ions from their production in the va-

por cell to the interaction region defined by the crossed laser and ion beams. Under this condition, any initial alignment should be randomized.

Electrons photodetached from the reference D^- and Li^- ions are known to have a $\cos^2\theta$ distribution for all values of the photon energy, i.e., the asymmetry parameter, $\beta=2$. In this case, the outgoing electron is represented by a pure p wave. The top part of Fig. 2 shows the angular distribution of electrons ejected in the photodetachment of a beam of Li^- ions via the $2\,^2S\epsilon p$ channel. This curve was used to calibrate the angle scale of the double Fresnel rhomb. Once the scale was calibrated, the asymmetry parameter characterizing the angular distribution of electrons detached from a beam of Be^- ions could be determined by measuring the yields of photoelectrons at just two angles, $\theta=0$ and 90°. The data is shown in the bottom part of Fig. 2. Small corrections were made to account for the finite solid angle of collection. One advantage of collecting electrons in the forward direction in angular distribution measurements is that the kinematic correction is angle independent for this arrangement. The only kinematic correction involves the change in solid angles of emission between the ion and laboratory frames, i.e., there is an enhancement of electron emission in the forward direction in the laboratory frame. The asymmetry parameter, measured at a photon energy of 2.076 eV, was determined to be 0.49 ± 0.02.

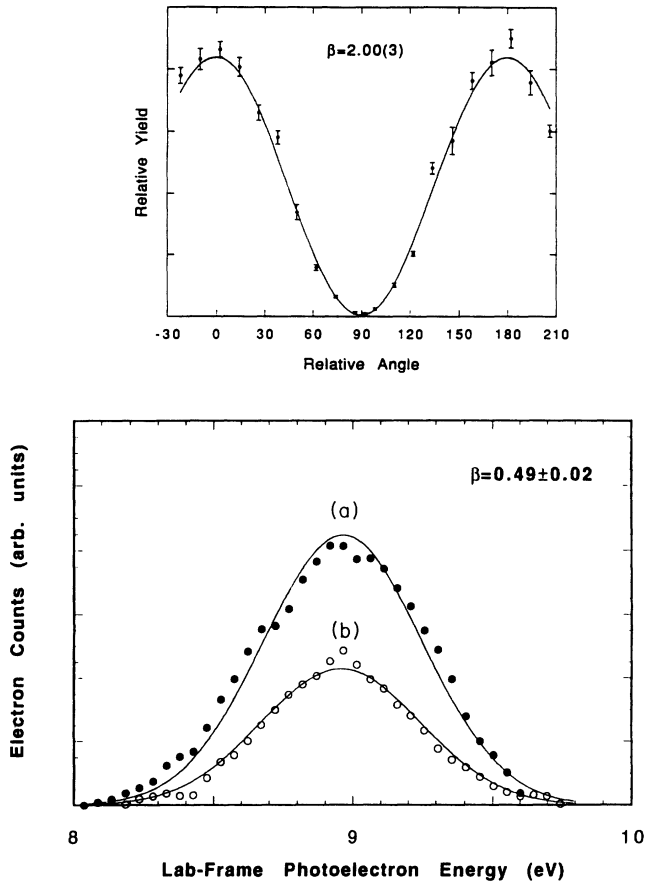

FIG. 2. Angular distribution of photoelectrons detached from beams of Li^- (top) and Be^- (bottom) ions. The Li-curve was used to calibrate the angle scale of a double Fresnel rhomb that is used to rotate the polarization vector of a laser beam. The asymmetry parameter β characterizing the electron angular distribution for Be^- photodetachment was determined from the asymmetry data shown in the bottom part of the figure. The spectral peaks correspond to the laser polarization being parallel (a) and perpendicular (b) to the direction of motion of the ion beam which is also the photoelectron collection direction. Angles are measured in degrees.

Figure 3 shows photoelectron spectra arising from the photodetachment of a beam of Be^- ions and a reference beam of D^- ions. At ion-beam energies of approximately 45 and 12 keV, respectively, the detached electron energy in the laboratory frame is about 9 eV in both cases. The apparatus is then equally efficient in collecting and detecting electrons from each beam. The experiment was repeated using a beam of Li^- ions as a reference. The velocities of both the ions of interest and the reference ions, which are needed to correct for differing ion-beam densities and kinematically-modified solid angles, were determined by comparing their photoelectron spectra with that obtained by photodetaching a reference beam of He^- ions at the same beam energy. Figure 4 shows, for example, electron spectra for Be^- (top) and He^- (bottom) photodetachment taken at a common ion-beam energy of 45 keV. The Be^- ion-beam energy can be accurately determined by measuring the separation of the two peaks in the He^- spectrum (corresponding to leaving the He atom in the $2\,^3S$ and $2\,^3P$ states following photodetachment) and the separation of the peak in the Be^- spectrum and either one in the He^- spectrum. Well-known values for the electron affinity of He ($2\,^3S$) and the $2\,^3S-2\,^3P$ transition energy were assumed. Details of this calibration method are found elsewhere [8].

The measured cross section ratios are $\sigma(Be^-)/\sigma(D^-)=0.90\pm0.12$ and $\sigma(Be^-)/\sigma(Li^-)$

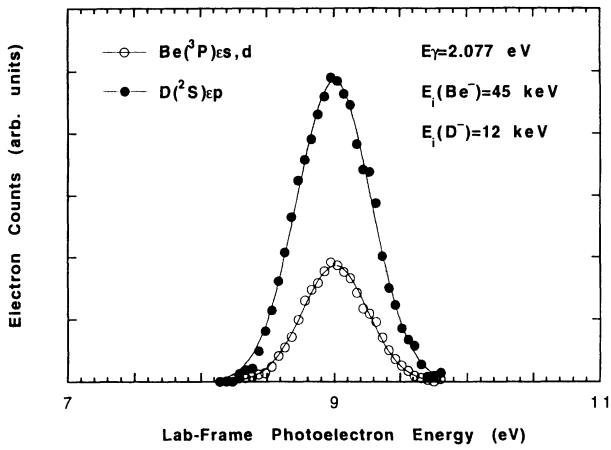

FIG. 3. Electron spectra arising from the detachment of beams of Be^- and D^- ions by photons of energy 2.076 eV. The D^- beam was the reference beam in this cross-section-ratio measurement. The ion-beam energies were chosen to kinematically shift the electron energies to the same value in the laboratory reference frame. Photoelectron yields are determined from the Gaussian-fitted peaks.

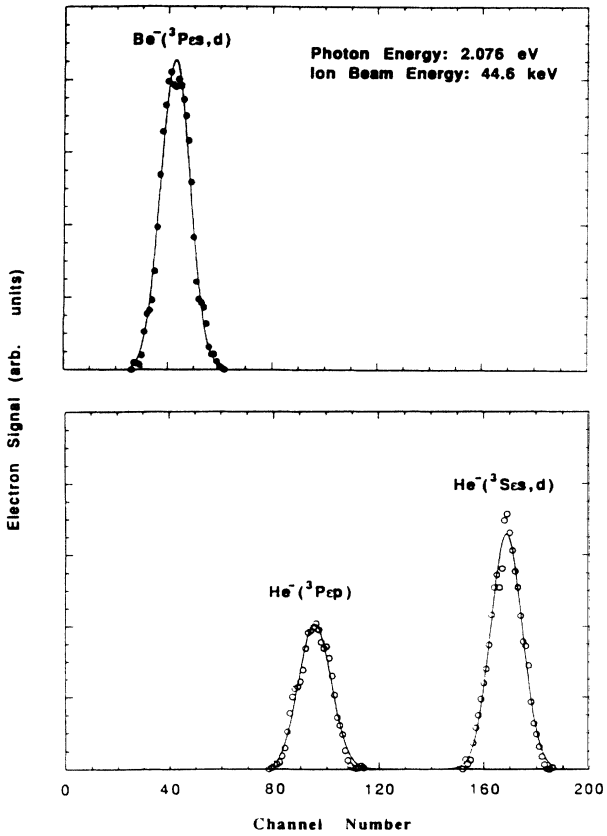

FIG. 4. Calibration of the Be^- ion-beam energy by use of electron spectra obtained by photodetaching, at the same beam energy, a beam of Be^- ions (top) and a reference beam of He^- ions (bottom).

$=0.50\pm0.05$. Each ratio was measured about a dozen times and the quoted uncertainty reflects the range of values in the data set about the weighted mean. The major source of these variations from measurement to measurement arose from small, but unavoidable, random changes in the overlap of the interacting beams. The $\sigma(Be^-)/\sigma(D^-)$ ratio was normalized to the theoretical value of $\sigma(H^-)=\sigma(D^-)=34.5\pm1.0$ Mb [9] while the $\sigma(Be^-)/\sigma(Li^-)$ ratio was normalized to the experimental value of $\sigma(Li^-)=63.5\pm5.7$ Mb. The latter result was obtained in an earlier experiment [10] by measuring the ratio $\sigma(Li^-)/\sigma(D^-)=1.84\pm0.11$. Thus, both measurements are tied, either directly or indirectly, to the theoretical value of the H^- (D^-) photodetachment cross section. Combining the results of the two ratio measurements, yields a weighted cross section of $\sigma(Be^-)=31\pm3$ Mb. This result is clearly at variance with the only other measurement of the quantity. Bae and Peterson [5] used interacting beams in a collinear geometry to measure the Be^- photodetachment cross section at several photon energies in the visible spectrum. They obtained a value of $\sigma(Be^-)=9\pm5$ Mb at approximately 2.076 eV. In contrast to the present relative measurement, the latter experiment was an absolute measurement. The large uncertainty limit quoted was primarily associated with the determination of the efficiency for detection of the neutral Be atoms used to monitor the photodetachment process.

IV. SUMMARY

We have measured, at a photon energy of 2.076 eV, the cross section for the single-photon detachment of an electron from the metastable Be^- ion via the process: $h\nu+Be^-(2\,^4P)\rightarrow Be(2\,^3P)+e^-(\epsilon s,d)$. The present value of $\sigma=31\pm3$ Mb is more than a factor of three larger than the only previously reported measurement of $\sigma=9\pm5$ Mb [5]. There are no theoretical predictions currently available to resolve the discrepancy. An investigation of the angular distribution of the detached photoelectrons was also performed in order to convert our angle-differential measurement into an integral one. The asymmetry parameter characterizing this angular distribution was determined to be $\beta=0.49\pm0.02$. This value, measured 1.8 eV above the channel threshold, reflects an interference between the outgoing s and d waves. At present, no theoretical values are available for comparison.

ACKNOWLEDGMENTS

The research was supported by the U.S. Department of Energy (DOE), Office of Basic Energy Sciences, Division of Chemical Sciences through the University of Tennessee and the Oak Ridge National Laboratory (ORNL). Oak Ridge National Laboratory is managed by the Martin Marietta Energy Systems, Inc. under Contract No. DE-AC05-84OR21400 with the U.S. DOE.

[1] K. Bethge, E. Heinicke, and H. Baumann, Phys. Lett. **23**, 542 (1966).
[2] A. W. Weiss, Phys. Rev. **166**, 70 (1968).
[3] A. V. Bunge, Phys. Rev. A **33**, 82 (1986).
[4] C. Y. Tang, J. R. Wood, D. J. Pegg, J. Dellwo, and G. D. Alton, Phys. Rev. A **48**, 1983 (1993).
[5] Y. K. Bae and J. R. Peterson, Phys. Rev. A **30**, 2145 (1984).
[6] P. Balling, L. H. Anderson, T. Anderson, H. K. Haugen, P. Hvelplund, and K. Taulberg, Phys. Rev. Lett. **69**, 1042 (1992).
[7] D. J. Pegg, J. S. Thomspon, R. N. Compton, and G. D. Alton, Phys. Rev. Lett. **64**, 278 (1990).
[8] D. J. Pegg, J. S. Thompson, R. N. Compton, and G. D. Alton, Nucl. Instrum. Methods Phys. Res. Sect. B **40/41**, 221 (1989).
[9] A. L. Stewart, J. Phys. B **11**, 3851 (1978).
[10] J. Dellwo, Y. Liu, C. Y. Tang, D. J. Pegg, and G. D. Alton, Phys. Rev. A **46**, 3924 (1992).