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Electron-impact ionization of Na

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Recent convergent close-coupling calculations of the ionization cross section of Na by Bray [Phys. Rev. Lett. **73**, 1088 (1994)] are in poor agreement with the experimental determinations, most of which were carried out in the 1960s. We report here a measurement of the ratio of the peak ionization cross section to the cross section for excitation of the $3\,^2P$ state near threshold. By normalizing the latter to the theoretical cross section computed by Moores and Norcross [J. Phys. B **5**, 1482 (1972)] and more recently by Trail *et al.* [Phys. Rev. A **49**, 3620 (1994)], we find an ionization cross section in agreement with Bray within 10%.

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A recent calculation of the ionization cross section of Na by Bray [1], using the convergent close-coupling (CCC) method, has proven to be in conflict with existing experimentally determined cross sections. Calculation of the *total* scattering cross section of Na using the same approach, on the other hand, appears to be consistent with experiment. Bray and Stelbovics [2] have shown previously that the CCC method is able to reproduce the ionization cross section of atomic hydrogen, and considering that applications to a number of spin-resolved properties of Na also gave excellent quantitative agreement with experiment [3], the fact that the predicted ionization cross section was approximately a factor of 2 lower than that found in the experiments [4–6] was surprising.

In view of the successes of the CCC method and the unsatisfactory level of agreement among the rather early ionization experiments, we have been motivated to report here, in brief form, the result of electron-scattering measurements of the ionization cross section of Na from threshold to 50 eV, normalized by reference to the cross section for electron excitation of the $3\,^2P$ state near threshold.

At the time these data were acquired, it was our intent to determine the excitation cross section using ionization cross sections which we believed could be more accurately measured. Instead, it now appears that the reverse is true. The early four-state close-coupling calculations of Moores and Norcross [7] for $3\,^2P$ excitation over the first 1 eV above threshold have recently been verified by 11-state calculations by Trail *et al.* [8]. Furthermore, the measurements of Enemark and Gallagher [9], corrected for cascade and normalized to Born cross sections at high energy, differ by only 7% from the theoretical value at 2.5 eV, the energy at which we normalize. As we show below, normalization of our excitation data to those of Moores and Norcross [7] yields a peak ionization cross section that lies well below previous measurements but approximately 10% above the calculated cross section of Bray [1]. This difference lies just inside our experimental error limits.

In this Rapid Communication only a brief outline of our experimental measurements can be given. An extensive description of the apparatus has been presented [10] and details of the Na measurement as well as our results in K and Rb will be submitted elsewhere. The apparatus consists of a magnetically collimated electron beam produced with a trochoidal monochromator [11]. The electron beam passes through a collision region consisting of two end plates and two C-shaped current collecting electrodes symmetrically placed on either side of the electron beam. A reasonably well collimated Na beam passes through the gap in the collecting electrodes and intersects the electron beam at right angles.

By appropriate bias on the end plates with respect to the collecting electrodes, two modes of operation can be utilized. With the end plates positively biased, only positive ions can reach the collectors, and the relative cross section for ionization may be traced out. By biasing the end plates negatively with respect to the collectors, the apparatus operates in the trapped electron mode [12]. With this technique, inelastically scattered electrons are trapped by the potential barrier at each end of the collision region. These slow electrons diffuse across the magnetic field lines by making successive elastic collisions and eventually reach the collecting plates. The relative excitation function of the $3\,^2P$ state can thus be observed from its threshold to an energy above threshold determined by the voltage applied to the end plates. In a crossed-beam apparatus, there are an insufficient number of elastic collisions outside the volume of the atomic beam to allow the trapped electrons to be collected. We solve this problem by introducing a static background of He vapor throughout the electron-beam apparatus.

To determine the shape of the inelastic excitation function accurately with the trapped-electron method, it is necessary to correct for the contribution from electrons that scatter elastically near 90° and become trapped and thus contribute to an increased scattering path length. The effect may be observed by repeating the measurements at several trapping well depths and noting the growth of the signal at a given energy above threshold. The correction procedure has been described in detail by Johnston and Burrow [10]. The present beam arrangement is more straightforward to treat than the static cell described earlier because of the limited region of collisions with Na atoms in the beam. Uncertainties in fitting the trapped electron data to the expression for the elastic correction contribute the major source of error, 11.6%, to the final measurement.

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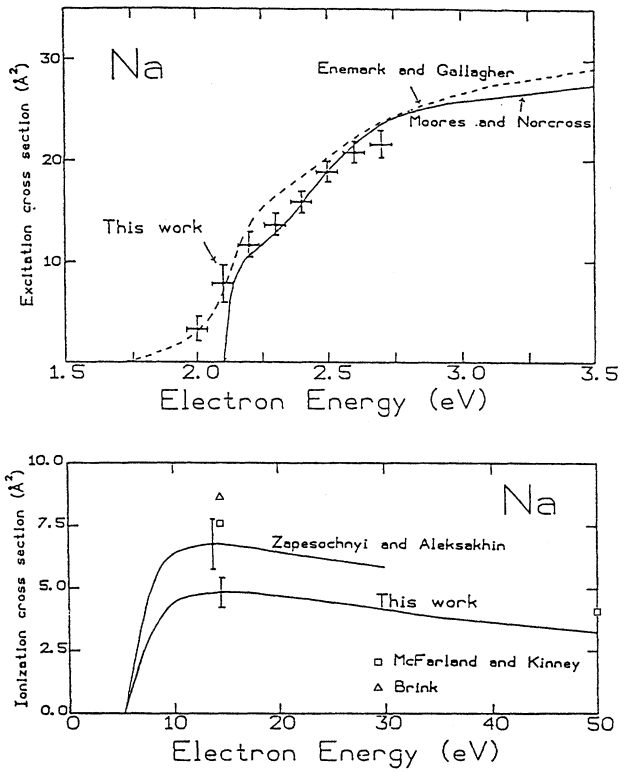

FIG. 1. Upper panel: total cross section for electron excitation of the $3\,^2P$ state of Na near threshold as a function of electron-impact energy. The present work is shown as discrete data points with error bars, the theoretical calculations of Moores and Norcross as a solid line, and the measurements of Enemark and Gallagher as a dashed line. The present work is normalized to that of Moores and Norcross at 2.5 eV. Lower panel: total cross section for ionization of Na as a function of electron energy as measured by Zapesochnyi and Aleksakhin, by the present work, and points from McFarland and Kinney, shown as open squares, and Brink, open triangle.

The ionization and trapped electron modes require only a change in the bias voltage to the end plates. Thus, the two measurements can be carried out in close order, minimizing the effects due to drifts in atom density, electron-beam current, and surface potentials that plague studies in the alkali-metal-atom vapors. In addition to the shapes of the excitation and ionization cross sections, the primary result is the ratio of the two cross sections determined at 2.5 eV for the excitation function, i.e., 0.4 eV above threshold, and near the peak of the ionization cross section at 13.8 eV. We find that

$$\frac{\sigma_{\rm ex}(3\,^2P,\ 2.5\ {\rm eV})}{\sigma_{\rm ion}(13.8\ {\rm eV})}=3.9\pm 13\%.$$

The upper portion of Fig. 1 displays the total cross section for excitation of the $3\,^2P$ state as a function of electron energy in the threshold region. The solid line shows the theoretical results of Moores and Norcross [7]. In the present report we have normalized our data points to this curve at 2.5 eV. The measurements of Enemark and Gallagher [9], shown as a dashed line, lie slightly higher. Using this calibration and the cross-section ratio given above, we find the total ionization cross section shown in the lower panel along with the earlier results of Zapesochnyi and Aleksakhin [5] and data points from McFarland and Kinney [4] and Brink [6]. The present data are listed in Table I.

TABLE I. The total ionization cross section of Na as a function of electron energy.

Energy (eV)	Cross section (Å²)
5.14	0.00
6.0	1.26
7.0	2.47
8.0	3.42
9.0	4.04
10.0	4.43
11.0	4.62
12.0	4.74
13.0	4.82
14.0	4.86
15.0	4.88
16.0	4.87
17.0	4.84
18.0	4.80
19.0	4.76
20.0	4.70
25.0	4.44
30.0	4.16
35.0	3.87
40.0	3.66
45.0	3.49
50.0	3.32

A detailed comparison with the theoretical ionization cross section calculated by Bray [1] is shown in Fig. 2. There is excellent agreement with regard to the energy of the peak cross section. The theoretical data, near the maximum, fall just inside the lower error limit shown on the experimental results, although it should be noted that normalization to the excitation function of Enemark and Gallagher would raise

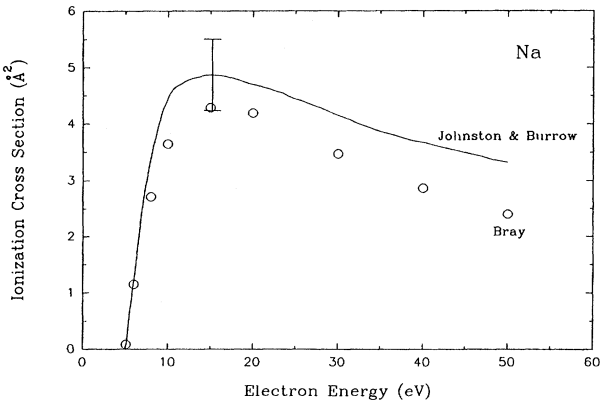

FIG. 2. Total cross section for ionization of Na as a function of electron energy. The present results are shown as a line, those calculated by Bray using the CCC method as open circles.

our ion cross section by about 7%. At higher energies the theoretical curve appears to fall off somewhat more rapidly with energy. Given that the calculations are more likely to underestimate the cross section at higher energies, the agreement appears to be satisfactory within the experimental uncertainties. In any case, we conclude that the present results remove most of the discrepancy between the CCC calculation and the experimental data.

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