or with a Baranger-Mozer–type perturbation spectrum. In particular, certain harmonics can be greatly emphasized without leading to high intensities elsewhere in the spectrum. In the recent experiments on the H_β line by Gallagher and Levine,[10] the observed satellite structure did not appear to conform to the simple Blokhintsev theory, and exhibited a much stronger second-harmonic intensity than predicted by the latter. Therefore, it seems to be warranted to seek an explanation of the Gallagher-Levine results along the lines of the present theory. In an actual plasma the fluctuating dynamic and quasistatic fields can be at arbitrary angles with respect to each other and their intensities are also distributed statistically. Quantitative comparison with experimental results, without taking into account these effects, would not be realistic. Detailed consideration of these aspects, and a more detailed theoretical analysis will be presented in forthcoming papers.

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[1]D. Blokhintsev, Phys. Z. Sowjetunion 4, 501 (1933).

[2]M. Baranger and B. Mozer, Phys. Rev. 123, 25 (1961).

[3]H.-J. Kunze and H. R. Griem, Phys. Rev. Lett. 179, 226 (1969).

[4]H.-J. Kunze, H. R. Griem, A. W. DeSilva, G. C. Goldenbaum, and I. J. Spalding, Phys. Fluids 12, 2669 (1969).

[5]W. W. Hicks, R. A. Hess, and W. S. Cooper, Phys. Rev. A 5, 490 (1972).

[6]L. Pauling and E. B. Wilson, *Introduction to Quantum Mechanics* (McGraw-Hill, New York, 1935), p. 138.

[7]S. H. Autler and C. H. Townes, Phys. Rev. 100, 703 (1955).

[8]P. Bakshi, to be published. For n simultaneous equations of the form of Eq. (2) the solution is similar to Eq. (3) with m independent frequency shifts k_i where $n=2m$ (n even), $n=2m+1$ (n odd).

[9]P. M. Morse and H. Feshbach, *Methods of Theoretical Physics* (McGraw-Hill, New York, 1953), p. 557.

[10]C. C. Gallagher and M. A. Levine, Phys. Rev. Lett. 27, 1693 (1971).

Observation of a Broad Resonance in the 2^3S Excitation of Helium by Electron Impact*

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We have observed a broad P-wave resonance at about 50 eV primary energy in the angular distribution of electrons scattered after excitation of the 2^3S state of helium. The resonance has a width of about 15 eV and affects the differential excitation cross section by more than 3 orders of magnitude. It is suggested that this resonance is associated with the temporary formation of triply excited states of the negative helium ion.

Narrow resonances in the 2^3S excitation cross section of helium just above threshold have previously been reported by Schulz and Philbrick[1] at an angle of 72°, and by Ehrhardt and Willmann[2] at angles between 7° and 110°. These resonances were also observed in the forward scattered electron current after excitation of the 2^3S state by Chamberlain and Heideman[3] and are associated with the formation of resonant states of doubly excited He^-.

Structure in the transmitted electron current at 57.1 and 58.2 eV, reported by Kuyatt, Simpson, and Mielszarek,[4] was interpreted by Fano and Cooper[5] as associated with the temporary formation of the triply excited states of He^-, $(2s^22p)^2P$ and $(2s2p^2)^2D$. Simpson, Menendez, and Mielczarek[6] investigated the angular dependence of narrow resonances in the 2^3S excitation due to these states.

All of the above resonances are extremely narrow, less than 100 meV, and give rise to small changes in the excitation cross section. In the present work a resonance has been observed with a width of about 15 eV, due to which the excitation cross section varies by more than 3 orders of magnitude.

The present apparatus is described in detail elsewhere.[7] Briefly, an electron gun produced a 1–5 μA beam of electrons with full width at half-maximum of 150 meV that interacted with the static target gas which was at a pressure of 1 mTorr. Electrons ejected at an angle θ with respect to the primary beam, with energy loss corresponding to excitation of the 2^3S state of

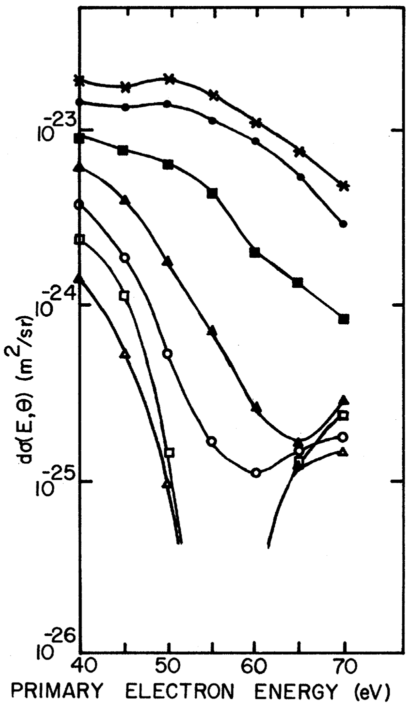

FIG. 1. Differential cross sections for electron excitation of the 2^3S state of He as a function of primary energy for angles between 25° and 80°. Asterisks, 25°; closed circles, 30°; closed squares, 40°; closed triangles, 50°; open circles, 60°; open squares, 70°; open triangles, 80°. The minima in the 70° and 80° curves are less than 4×10^{-26} m^2/sr.

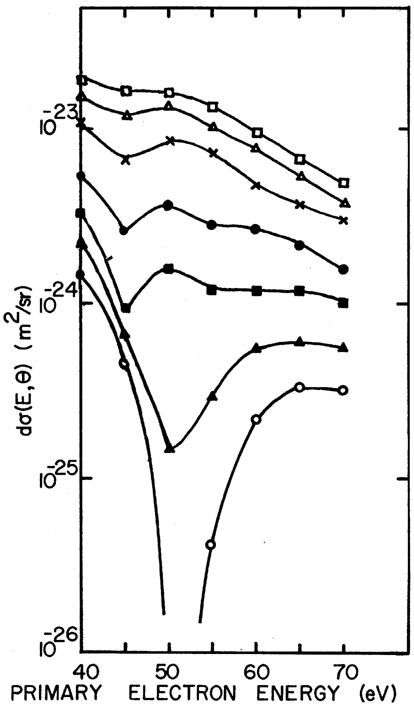

FIG. 2. Differential cross section for electron excitation of the 2^3S state of He as a function of primary energy for angles between 90° and 150°. Open circles, 90°; closed triangles, 100°; closed squares, 110°; closed circles, 120°; crosses, 130°; open triangles, 140°; open square, 150°. The minimum in the 90° curves is less than 5×10^{-27} m^2/sr.

helium, were selected by a parallel-plate analyzer with an energy resolution of 0.35%, and detected by a channel electron multiplier. The angle θ was varied by rotating the electron gun with respect to the analyzer entrance slits.

Figures 1 and 2 show the measured cross sections for excitation of the 2^3S state of helium as a function of primary energy E for fourteen angles between 25° and 150°. The cross sections were placed on an absolute basis by normalization to the 50-eV data of Ref. 7. The uncertainty in the absolute value of the cross sections is less than ±30%, and the internal consistency is better than ±10%. An upper limit of 4×10^{-26} m^2/sr has been placed on the cross sections at 55 and 60 eV at both 70° and 80°, and 5×10^{-27} m^2/sr at 50 eV and 90°.

Figure 3 shows the total excitation cross section for the 2^3S state of helium, obtained by integration of the data shown in Figs. 1 and 2. The maximum in the total cross section occurs at the same energy as the minima in the differential cross sections, indicating that the process producing the minima cannot be one of simple interference, but rather the effect of a broad resonance.

The differential cross section can be approximated by

$$d\sigma(E,\theta)=(1/E)\left|\textstyle\sum_L(2L+1)T_L(E)P_L(\cos\theta)\right|^2,$$

where T_L is the transition matrix for excitation of the 2^3S state of helium from the ground state, containing both real and imaginary elements for each L value. Fitting this equation to the experimental data at each energy, Macek and Wooten[8] have extracted the elements of the T matrix for the first four partial waves with a χ^2 of about 1 per point. Further analysis is required, but the preliminary results indicate that the S, D, and F waves are fairly constant with the S- and D-wave contributions destructively interfering at 90°, while the P-wave amplitude and phase vary rapidly in this energy range, identifying the major effect as a broad P-wave resonance.

The width of the resonance indicates that it is not due to the temporary formation of the two

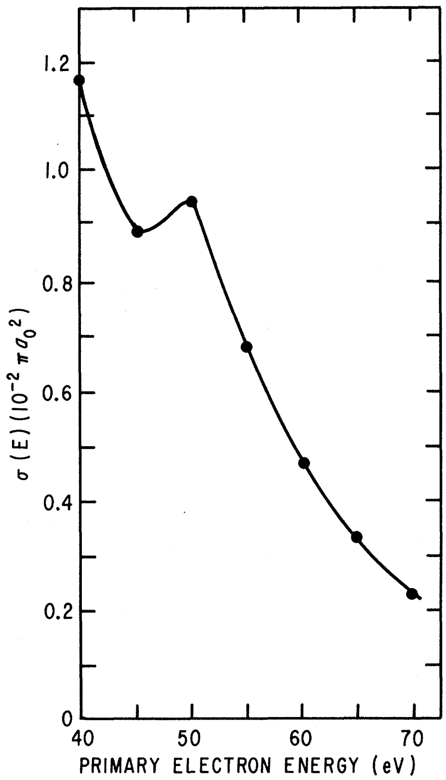

FIG. 3. Total cross section for electron excitation of the 2^3S state of He as a function of primary electron energy.

previously observed states of He^-, $(2s^2 2p)$ and $(2s2p^2)$, but possibly to the compound states, $2s(2snp \pm 2pns)$. While these states correspond to narrow resonances in Li, they need not correspond to narrow resonances in the isoelectronic sequence of He^-. In a comparison of He and H^- resonances, it has been found[9] that the (+) series of narrow resonances in He corresponds to a single broad resonance in the isoelectronic sequence of H^-. Measurements of the cross sections differential in primary energy and angle for excitation of all the singly excited states of helium over larger energy domain are in progress.

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[1]G. J. Schulz and J. W. Philbrick, Phys. Rev. Lett. 13, 477 (1964).

[2]H. Ehrhardt and K. Willmann, Z. Phys. 203, 1 (1967).

[3]G. E. Chamberlain and H. G. M. Heideman, Phys. Rev. Lett. 15, 337 (1965).

[4]C. E. Kuyatt, J. A. Simpson, and S. R. Mielczarek, Phys. Rev. 138, A385 (1965).

[5]U. Fano and J. W. Cooper, Phys. Rev. 138, A400 (1965).

[6]J. A. Simpson, M. G. Menendez, and S. R. Mielczarek, Phys. Rev. 150, 76 (1966).

[7]G. B. Crooks, Ph. D. thesis, University of Nebraska, 1972 (unpublished).

[8]J. Macek, private communication.

[9]J. Macek and P. G. Burke, Proc. Phys. Soc., London 92, 351 (1967).

Energy Shifts and Relative Intensities of *K* X Rays Produced by Swift Heavy Ions*

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The energy shifts of Fe, Co, Zr, and Sn *K* x rays produced by 5-MeV/amu He, C, O, Ne and 10 MeV/amu C ions depend nearly linearly on the stopping power for the bombarding ion. The shifts and the $K\beta/K\alpha$ ratios show a projectile energy dependence similar to that predicted for the *L*-ionization cross section. This suggests that these phenomena can be explained by existing Coulomb excitation theories.

Weak satellites associated with *K* lines were first discovered by Siegbahn and Stenström,[1] and an explanation involving multiple inner-shell ionization was proposed by Wentzel.[2] More recently the observation of energy shifts in the $K\beta$ lines of Cu and Ni induced by 15-MeV O bombardment has been reported by Richard *et al.*[3] using a Si(Li) detector for measuring the x-ray energies. They ascribe the shifts to multiple inner-shell ionization, an explanation which has been verified by Bragg spectrometer experiments in which the measured lines were resolved into satellites cor-