Angle and Channel Dependence of Resonances in e-He Scattering near 60 eV*

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The He^- resonances at 57.1 and 58.2 eV in the electron scattering from He were studied as a function of angle in three inelastic channels corresponding to excitation of the $(1s2s)^3S$, $(1s2s)^1S$, and $(1s2p)^1P$ states of He. The line shapes of the resonances are found to vary with angle. The application of the Fano-Cooper formula, developed for the case of photon absorption, to resonances in inelastic electron scattering is discussed, along with a simple procedure for determining the line profile indices. The angular dependence of the ^1S, ^3S, and ^1P excitations at 56.5 eV was also measured out to about 60°.

IT has been shown by Chamberlain[1] that the existence of negative-helium-ion states in the 20–25-eV region gives rise to a number of sharp structures (resonances) in the cross section for the excitation by electron impact of the $(1s2s)^3S$, $(1s2s)^1S$, $(1s2p)^3P$, and $(1s2p)^1P$ states of neutral helium. The large number of resonances found in the inelastic channels suggests that they may be a widely occurring feature of these cross sections. These resonances are much more apparent in the inelastic channels[2] than in transmission measurements[3]; they have been observed in H_2 (Ref. 4) and N_2 (Ref. 5) as well as in He. We have therefore made a study of the excitation functions of the $n=2$ He states in the 56.5- to 59-eV region, where Kuyatt *et al.*[6] had observed barely detectable resonances in the transmission channel, and furthermore, we have investigated the dependence of these resonances upon the scattering angle.

For this work there was available a scattering instrument similar in concept to the one previously described[7] but with a scattering chamber constructed of a metal bellows that permitted mechanical rotation of the monochromator beam axis with respect to the analyzer. By this arrangement scattering angles of $-10°$ to $90°$ could be explored. The angular resolution of the device is less than 1° and for these measurements the energy resolution was approximately 0.1 eV. Earlier applications of this instrument had not exploited its angular capabilities.[8] The effect of the He^- states at 57.1 and 58.2 eV, interpreted as having the configurations $(2s^22p)^2P$ and $(2s2p^2)^2D$, respectively,[9] on the excitation cross sections of the ^3S, ^1S, and ^1P states was examined by sweeping the primary electron energy between 56.5 and 59.0 eV with the analyzer set to pass only those electrons that had suffered the particular energy loss corresponding to excitation to one of the $n=2$ states. Two resonances were indeed observed in each of these channels; however, the resonances in the ^3P channel were not amenable to study because of overlap from the nearby ^1P channel which has a larger cross section. No effect of the resonances was found in the elastic channel at angles $\gtrsim 3°$, where it becomes possible to separate this channel from the inelastic channels.

In Fig. 1 are shown some typical line shapes of the two resonances in the three inelastic channels at various fixed angles. Figure 1 shows the qualitative features of the line shapes; the quantitative aspects of these resonances are given in Figs. 2 and 3. These line shapes bear a strong resemblance to the Fano line shapes[10] derived for the case of photon absorption. In view of this resemblance it seems desirable to adopt the terminology and definitions developed for the photon absorption case to the present situation of negative ion resonances in inelastic electron scattering. Justification for this procedure can be obtained from the following analysis suggested by Fano.[11]

We initially assume that the scattering amplitude for a well-defined process depends on the incident energy E in the neighborhood of a resonance at E_0, according to

$$\text{Scattering Amplitude}=a+b(E-E_0+\tfrac{1}{2}i\Gamma)^{-1}, \quad (1)$$

where a and b are complex coefficients and Γ is the resonance width. The coefficient a can be any function of energy except that the variations of a are regarded as negligible when E varies by a few Γ. Equation (1) has the general form of a resonance and special cases of this formula are found in treatments of resonance

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[1] G. E. Chamberlain, Phys. Rev. Letters 14, 581 (1965).
[2] G. E. Chamberlain and H. G. M. Heideman, Phys. Rev. Letters 15, 337 (1965).
[3] Transmission measurements are measurements at 0° of the current of electrons that have suffered no energy loss; therefore, it is a measure of $(1-\sigma_t)$, where σ_t is the total cross section. This particular measurement will be referred to as measurements in the transmission channel.
[4] G. J. Schulz, Phys. Rev. 135, A988 (1964); H. G. M. Heideman, C. E. Kuyatt, and G. E. Chamberlain, J. Chem. Phys. 44, 440 (1966).
[5] G. J. Schulz, Ref. 4; H. G. M. Heideman, C. E. Kuyatt, and G. E. Chamberlain, J. Chem. Phys. 44, 355 (1966).
[6] C. E. Kuyatt, J. A. Simpson, and S. R. Mielczarek, Phys. Rev. 138, A385 (1965).
[7] J. A. Simpson, Rev. Sci. Instr. 35, 1698 (1964).
[8] J. A. Simpson, G. E. Chamberlain, and S. R. Mielczarek, Phys. Rev. 139, A1039 (1965).
[9] U. Fano and J. W. Cooper, Phys. Rev. 138, A400 (1965).
[10] U. Fano, Phys. Rev. 124, 1866 (1961).
[11] U. Fano (private communication).

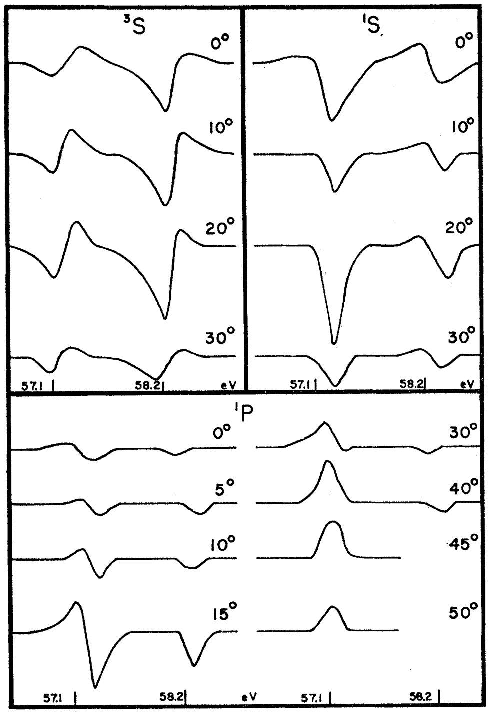


FIG. 1. Typical line shapes of the 57.1- and 58.2-eV He⁻ resonances in the ^3S, ^1S, and ^1P inelastic channels at various angles. The current scale is in arbitrary units with the zeros displaced. The energy scale is accurate to about 0.2 eV.

collisions.[12] Taking the cross section of the process to be proportional to the square of the scattering amplitude one obtains

$$\sigma=C\,|a|^2\left[1+\frac{4\,|u|^2-\mathrm{Re}u+\epsilon\,\mathrm{Im}u}{(1+\epsilon^2)}\right], \tag{2}$$

where $\epsilon=(E-E_0)/(\frac{1}{2}\Gamma)$ and $u=ib/a\Gamma$. This equation has the form of the Fano-Cooper formula[13]

$$\sigma(\epsilon)=\sigma_a[(q+\epsilon)^2/(1+\epsilon^2)]+\sigma_b\,, \tag{3a}$$

which upon expansion yields

$$\sigma(\epsilon)=(\sigma_a+\sigma_b)\left\{1+\rho^2\left[\frac{(q^2-1)+2q\epsilon}{(1+\epsilon^2)}\right]\right\}, \tag{3b}$$

where $\rho=\sigma_a/(\sigma_a+\sigma_b)$, σ_a is the resonant portion of the cross section, σ_b is the nonresonant portion, and q is a line profile index. Comparison of (2) and (3b) yields the following relationships:

$$C\,|a|^2=(\sigma_a+\sigma_b)\,, \tag{4a}$$

$$\rho=2\,\mathrm{Im}\{[(u-1u)^*]^{1/2}\}\,, \tag{4b}$$

$$q=\mathrm{Re}\{[(u-1)u^*]^{1/2}\}/\mathrm{Im}\{[(u-1)u^*]^{1/2}\}\,. \tag{4c}$$

[12] See for example, M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952).
[13] U. Fano and J. W. Cooper, Phys. Rev. **137**, A1364 (1965).

Equation (1) still remains to be derived from first principles of scattering theory; however, because of the correspondence of Eq. (3) (which is based on strong theoretical grounds for photon absorption) to the more general form of a cross section near a resonance [Eq. (2)] we feel that the use of the Fano-Cooper formula for negative-ion resonances is indicated.

We wish then to turn to the Fano-Cooper formula [Eq. (3)] wherein the natural line shape of a resonance is given by $(q+\epsilon)^2/(1+\epsilon^2)$. This function possesses a maximum when $q=1/\epsilon$, and a minimum when $q=-\epsilon$ with a total excursion through the resonance of $(1+q^2)$. In absolute units the total excursion of the resonance is given by $\sigma_a(q^2+1)$. A measure of the strength of the resonance can be represented by normalizing the resonant portion $\sigma_a(q^2+1)$ to the off-resonance value of the cross section $(\sigma_a+\sigma_b)$. This normalized strength is given by

$$[\sigma_a/(\sigma_a+\sigma_b)](q^2+1)=\rho^2(q^2+1)\,, \tag{5}$$

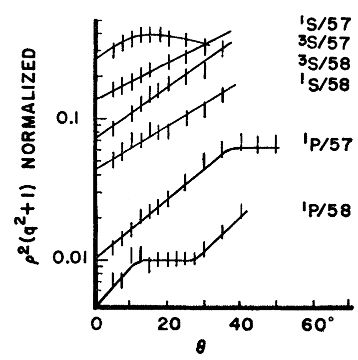
where ρ^2q^2 represents the fractional rise above the off-resonance value, ρ^2 represents the fractional trough, and q is given by the square root of the rise-to-trough ratio.

The cross sections discussed thus far, being proportional to the squared scattering amplitude for a well-defined process, pertain by implication to transitions between initial and final states with complete specification of energy, direction, and polarization of all reactants. In practice one deals with transitions from a suitably averaged initial state to a suitably averaged weighted sum of final states. The relevant cross section is summed accordingly. The experimental cross section thus determines the coefficients of the terms in (3b), namely, the suitably sum-average values

$$\langle(\sigma_a+\sigma_b)\rangle,\quad \langle(\sigma_a+\sigma_b)\rho^2(q^2-1)\rangle,\quad \langle(\sigma_a+\sigma_b)\rho^2 2q\rangle. \tag{6}$$

From these values one obtains effective values of ρ and q. These effective values can be extracted from the data by use of Eq. (5); however, these values also contain experimental smearing effects due to finite energy resolution, initial energy spread, and Doppler broadening. For example, Lorentzian smearing transforms $\rho^2(q^2+1)$ into $\rho_s^2(q^2+1)$, which is inversely pro-

FIG. 2. Logarithm of the effective strength of the resonance, $\rho^2(q^2+1)$, normalized to the off-resonance cross section at 56.5 eV in the ^3S, ^1S, and ^1P channels as a function of angle. The vertical line denotes the estimated error.



portional to Γ_s, where Γ_s is the width of the observed resonance, but leaves q unchanged.[14] For Gaussian smearing approximately the same effects are found as for Lorentzian smearing.

This description of resonance line shapes greatly simplifies the analysis of the data. For example, the necessity of a curve-fitting procedure employed previously[10] is not necessary for the determination of the effective line-profile indices ρ and q; however, a complete description of the resonance requires the determination of Γ which does require this prodedure. All that is needed to obtain effective values of the line-profile indices is (i) the resonance effect, (ii) an estimate of the smooth portion of the cross section through the resonance region.

The effective strengths of the resonances $\rho^2(q^2+1)$ for each of the three channels are shown in Fig. 2 as a function of angle. In all the channels except for the 57.1-eV resonance in the 2^1S channel ($^1S/57$) and the $^1P/58$, the resonance strength appears to rise as a straight line up to about 50°; the $^1S/57$ and $^1P/58$ resonances exhibit a local maximum around 15°. Effective values of q are shown in Fig. 3. The effective q's are seen to increase linearly in all the channels except for the $^1P/57$ resonance, which exhibits a maximum around 10°.

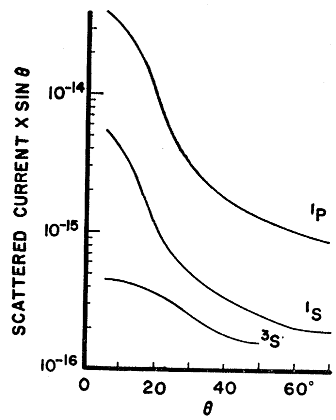


FIG. 4. Logarithm of the relative cross section at 56.5 eV versus angle for the ^3S, ^1S, and ^1P excitations.

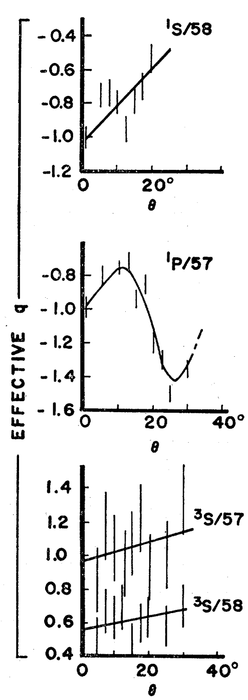


FIG. 3. Effective values of q versus angle. The effective q's of the $^1S/57$ and $^1P/58$ resonances are not shown since they were found to be zero. The effective q for the $^1P/57$ was found to rise rapidly beyond 30° (the rise is not shown above).

To obtain a relative cross section as a function of angle the scattered current was multiplied by the sine of the scattering angle to correct for a change in active path length. The resulting curves for the off-resonance signal at an incident energy of 56.5 eV are shown in Fig. 4 for the three excited levels. The nonresonant portion of the cross section is expected to be largest for the optically allowed 2^1P excitation, which can include important contributions from partial waves with moderately large l values (~ 5), next largest for 2^1S, and smallest for 2^3S whose excitation requires electron exchange and, therefore, $l \lesssim 2$. The results in Fig. 4 agree generally well with this expectation. It will also be noted that these channel differences are found to be decreasing at large angles, where high-l contributions tend to interfere destructively. These observations are not inconsistent with the assignment of $l=1$ and 2 to the 57- and 58-eV resonances, respectively.

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[14] J. W. Cooper (private communication).