Observation of Threshold Effects in Positron Scattering from the Noble Gases

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Channel coupling is a phenomenon that has been investigated for many scattering processes, and is responsible for the formation of cusps or steps in the cross sections for open scattering channels at, or near, the onset of a new scattering channel. It has long been speculated that the opening of the positronium formation channel may lead to the formation of such cusp features in the elastic positron scattering cross section. In this work, elastic scattering of positrons has been measured in the region of the positronium formation threshold for the noble gases He-Xe. Cusplike behavior is observed and, while the features which are observed appear broad, they represent a magnitude of between 4 and 15% of the total elastic cross section. No evidence is found of any other features in this region, at least within the uncertainty of the present data, discounting the possibility of scattering resonances.

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In 1948, E. Wigner first predicted the presence of cusps in nuclear scattering cross sections, at the threshold of new scattering channels. This process is also applicable to electron or positron scattering, and these cusps could, in principle, be present in any channel which is open prior to the onset of a new scattering channel [1], although in practice they are only discernible provided the new channel opens strongly. The size of such features is expected to depend on the rate of increase of the cross section for the new channel above the threshold. As electron beam experiments became more commonplace both theoretical and experimental evidence for such features was established in electron scattering processes (see [2–4], for example).

Indeed, the observation of threshold cusps for low energy electron scattering from the alkalis [5] provides an interesting comparison for the present investigation of positron interactions, in which we probe channel coupling at the threshold for positronium (Ps) formation. In the case of the alkalis [5], the cusp effects are seen at the opening of the strong n^2P resonance transitions (e.g., $n = 3$ for Na), which represent the overwhelming majority of the oscillator strength for these atoms [5]. The strong opening of these scattering channels is matched by marked cusp effects in the only other open channel, that for elastic scattering. In a similar fashion, Ps formation represents the major inelastic scattering channel for positron interactions with the rare gases at low energies, and predictions of strong cusp behavior in the elastic positron scattering channel at this threshold are entirely consistent with the electron scattering situation.

The search for such cusps in positron scattering was first undertaken in 1987 by Campeanu *et al.* [6] in the region of the Ps formation threshold energy in scattering from helium. An elastic cross section was derived from analysis of separate experimental results for Ps formation and the grand total cross section. The resultant elastic cross section peaked at the threshold, then dropped away by ~20% across the Ore gap. In 1992, Coleman *et al.* investigated this region by measuring both the Ps formation and grand total cross sections in a transmission based apparatus [7]. The 20% drop speculated by Campeanu *et al.* was not reproduced. However, due to the resolution limitations of their experiment, the presence of a cusp could not be ruled out. Interestingly, Coleman *et al.* did observe a step in the data, at an energy roughly corresponding to the onset of the 2^1S excitation. In 2009, higher resolution measurements by Caradonna *et al.* reported a weak cusp feature in the elastic cross section at the Ps formation threshold [8]. Those results are in reasonable agreement with those of Coleman *et al.* up to the first excitation threshold at 20.6 eV, showing a decrease through the Ore gap of no greater than 5%. After the Ore gap, the elastic cross section measurements diverge, with the data of Coleman *et al.* showing a step, which is not reproduced in that of Caradonna *et al.*. A feature has also been reported by Karwasz *et al.* [9] in the total cross section but below, in energy, the Ps formation threshold.

Semiempirical and theoretical investigations of cusp phenomena at the Ps formation threshold have been conducted in the noble gases. The study by Meyerhof and Laricchia [10] predicted an increasingly strong cusp through the noble gas series, which was effectively in line with elastic cross sections derived in the same work through subtraction of available grand total and Ps formation cross sections. Van Reeth and Humberston [11] calculated a small cusp in the elastic cross section at the threshold of Ps formation in positron scattering from helium, using a variational approach, although this was much smaller and qualitatively different from other predictions and observations.

The present work is motivated, in part, by the recent results of Coleman *et al.* [12] who reported the presence of a sharp step at the onset of Ps formation in Xe, as well as a smaller, more cusplike feature seen in Ar. The features observed in Ar and Xe were suggested to potentially result from enhanced elastic scattering, resulting from an intermediate process in the interaction involving virtual Ps formation.

The apparatus and experimental techniques used in the present measurements have been discussed in detail elsewhere [13,14] and so will only be briefly discussed here. Positrons are obtained from a 50 mCi ^{22}Na source, moderated through a solid neon layer grown in the vicinity of the source capsule. Moderated positrons are then separated from the unmoderated positrons and magnetically and electrostatically guided to a Surko buffer gas trap. Positrons are radially confined throughout the experiment by axial magnetic fields. A pulsed beam is created from the trap with an energy resolution of 50–70 meV, cycled at around 100 Hz with approximately 1000 positrons per pulse. A retarding potential analyzer (RPA) is positioned downstream of the scattering cell and is used to determine the energies of the scattered positrons. The accuracy in the absolute energy scale is estimated to be better than 50 meV. This calibration has been found to agree well with the known threshold energy of Ps formation. Positrons passing through the RPA are collected with a microchannel plate assembly, allowing the measurement of the transmitted intensity as a function of the retarding potential.

To determine the cross sections described in this work, a number of measurements of the transmitted intensity are required. A measurement of the full incident intensity of the beam, I_0, is made when the potential applied to the scattering cell defines a scattering energy below the Ps formation threshold, and with the RPA potential set to 0 V, allowing all positrons through to the detector. Adjusting the potentials on the scattering cell, and at the RPA, it is possible to measure the grand total, total Ps, and total elastic cross sections [8,14].

The total cross section is given via the Beer-Lambert attenuation law:

$$\sigma_{\mathrm{GT}} = \frac{-1}{n_m l} ln\left(\frac{I_T}{I_0}\right). \tag{1}$$

In the above formula, I_0 is the full incident intensity, I_T is the transmitted, unscattered intensity, n_m is the gas number density, dependent on the pressure and temperature of the gas within the cell, and l is the scattering path length, taken to be equivalent to the length of the scattering cell, which was 200 mm for these experiments. Typical pressures range from 0.1 to 10 mTorr. Systematic errors from the pressure measurement range from 1–7% depending on the pressure of gas used and, combined with the statistical uncertainty of the measurement, form the main source of error. The Ps formation and elastic cross sections are calculated as fractions of the grand total as follows:

$$\sigma_{Ps} = R_{Ps}\sigma_{\mathrm{GT}} \tag{2}$$

$$\sigma_{\mathrm{el}} = R_{\mathrm{el}}\sigma_{\mathrm{GT}} \tag{3}$$

where in the above partial cross section formulae R values are given by the fraction of the total attenuation resulting from Ps formation (Ps) and elastic scattering (el).

The present results for He, Ne, Ar, Kr, and Xe are presented in Fig. 1. For clarity, measurements of the cross sections performed by other groups have been omitted.

A clear peak can be observed in the elastic cross section for each target, as seen in Fig. 1, centered on the Ps formation threshold. Statistical uncertainty in the elastic cross section is less than 2% for each target, and can be estimated from the scatter in the data points. The dashed curve in each plot represents a fit to the data, using an idealized peak shape (in this case a Lorentzian profile) with a variable magnitude, width, peak position, and background cross section. Using this technique, we can confirm both the position of the peak and the magnitude, relative to the smoothly varying background. For all targets investigated in the study, the peak is centered on the Ps formation threshold within the error of the fit, approximately 90 meV. The relative magnitude of the peak varies for each target, with a relative magnitude of 11 $\pm$ 1.0% for helium, 4.1 $\pm$ 1.0% in neon, 9.0 $\pm$ 1.0% in argon, 7.7 $\pm$ 1.0% in krypton, and 15 $\pm$ 1.0% in xenon.

The observed features unambiguously indicate broad Wigner cusps in the elastic scattering channel for all five noble gases studied. These cusps appear to be broader than those typically seen in electron scattering, with the positron features extending over a range of 1–3 eV, while cusps seen in electron scattering typically extend over 0.5 eV or less (see, for example, [2,3,5,15]). The observed features are almost certainly the result of virtual Ps formation, as has been suggested previously in the work of Coleman *et al.* [12] as well as in the theoretical treatment of Meyerhof and Laricchia [10]. While the present results more closely follow the predicted behavior outlined in the latter work, it would appear that there is not a strong correlation between the mass of the atom and the observed features.

In Fig. 2(a), the present result for He is shown alongside the data of Coleman *et al.*, which have been scaled by a factor of 0.93 for comparison with the present data, as well as the theoretical predictions of Van Reeth and Humberston [11] and the total cross section measurement of Karwasz *et al.* [9]. It can be seen that the present result is in very good agreement with the data of Coleman *et al.* in this region of overlap, although it must be noted that higher energy data, above 21 eV, have been published previously that do not indicate the large step seen in the Coleman data [8]. The variational calculations of Van Reeth and Humberston predict a narrow downward cusp in the elastic cross section at the Ps threshold. The feature observed in the present data however is much larger and broader than the theoretical prediction, even accounting for broadening due to the energy resolution. Karwasz *et al.* observe what appears to be a small bump in the total cross section but at an energy which is 1–2 eV below the Ps formation thresh-

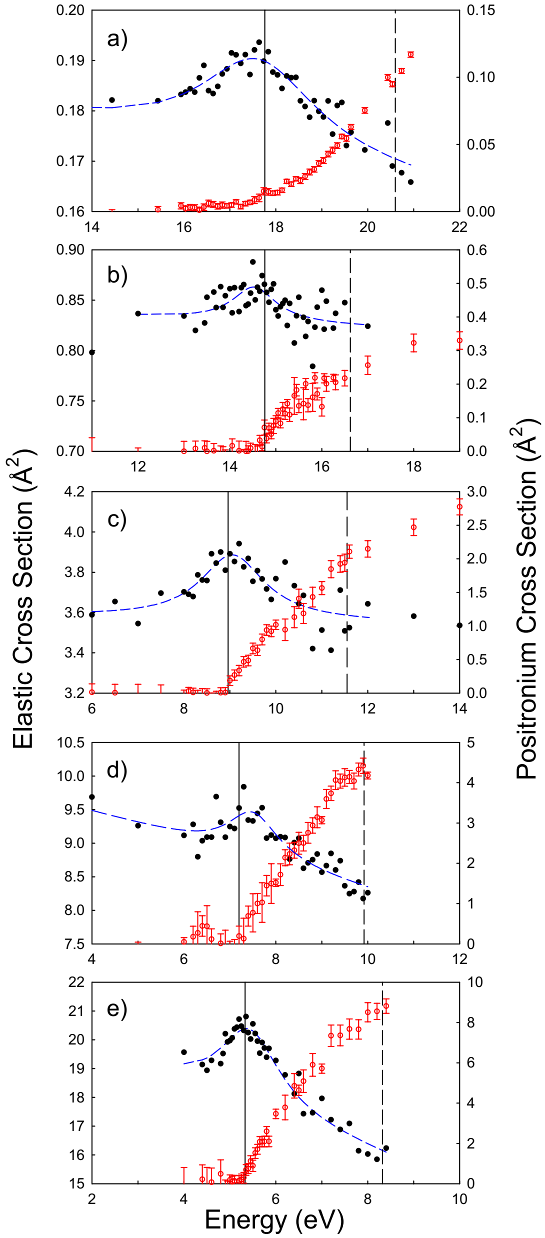

FIG. 1 (color online). ● Elastic cross section, ○ Ps formation cross section, — 5-Parameter Lorentzian fit, (a) e^+-He, (b) e^+-Ne, (c) e^+-Ar, (d) e^+-Kr, (e) e^+-Xe. Where shown, error bars represent 1 standard deviation. Solid black vertical lines indicate the Ps formation threshold, while the dashed vertical lines indicate the first excitation threshold.

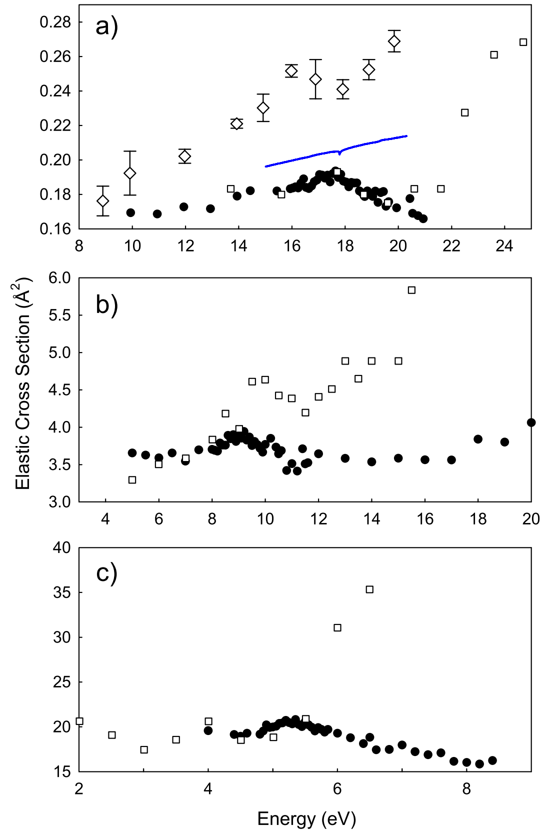

FIG. 2 (color online). Elastic cross section: ● Present data, □ Coleman *et al.* (He—[7], Ar and Xe - [12]), —Van Reeth & Humberston variational calculation [11], ◇ Grand total of Karwasz *et al.* [9]. (a) e^+-He, (b) e^+-Ar, (c) e^+-Xe.

old. We do not observe such a feature in our total cross section [8]. In Fig. 2(b), we show the corresponding comparison for argon with the recent measurements from [12], which have been scaled by a factor of 1.32. While the energy dependence of the background cross section in each of the two measurements is clearly different, the cusp at the Ps formation threshold appears in both sets of data. However, the data of [12] exhibit a substantially larger increase in the elastic cross section through the region of the Ps threshold, and another substantial increase above the Ore gap—neither feature being observed as strongly in the present data. Finally, in Fig. 2(c), we compare our results for Xe with the recent data of [12] and find the largest differences in both magnitude and energy dependence of the total elastic cross section. In this case, the data of [12] have been scaled by a factor of 2.45 for comparison with the present cross section. Aside from the large difference in magnitude, the two cross sections have a markedly different energy dependence above the Ps threshold, with the present cross section dropping some 22% across the Ore gap while that of Coleman *et al.* increases by about a factor of 2.

While there is no clear evidence of Wigner cusps in the previously published work [12], the data for helium and argon are, at least, not inconsistent with the behavior observed in the present data. In the case of xenon, however, the previous measurements show no sign of the cusp, despite the fact that it is most prominent for this target, among those that have been studied here.

We note a further interesting feature of the present measurements is that the total cross section values for krypton and xenon, in particular, are considerably greater in magnitude than those measured previously [16–19]. One possible reason for this was thought to be angular resolution effects and, in the case of the present measurements, the angular resolution is considerably better than previous experiments (e.g., 6.3° at 8 eV). With the present experimental technique, we are able to "degrade" our angular resolution in a straightforward manner (as discussed in Sullivan *et al.* [14]) and can compare the resulting cross sections directly with previous measurements, for example, those of Dababneh *et al.* [18], which were taken with a stated angular resolution of 20°, for positron scattering from Xe. When this comparison is made, the magnitudes of the measured cross sections are in excellent agreement. This indicates that the shape of the differential cross section in this energy range is strongly forward peaked, and the "missing" forward scattering can have a profound effect on the measured total cross section. This proposition is also in agreement with the calculations and measurements of Marler *et al.* [20] for differential positron-Xe scattering. If we use the calculated differential cross section in Marler *et al.* to model the total scattering cross section, then removing the forward 20° of angular scattering reduces the total cross section by approximately 35% at an energy of 8 eV. This is completely consistent with what is seen in the comparison between the present measurements and previously published work. The same arguments are also relevant to the krypton measurements presented here. A full exploration of this effect will be presented in a future publication on positron scattering from the noble gases.

In conclusion, the results presented here for elastic scattering from the rare gases He–Xe, in the region of the Ps formation threshold, display a series of cusp features centered at the threshold. The size of the cusp varies depending on the target, but there is no clear trend for the magnitude of the cusp as a function of atomic number, in contrast to the predictions of Meyerhof and Laricchia [10]. These features are a direct result of strong channel coupling between the elastic and positronium formation channels and are a clear experimental signature of virtual positronium formation, which has long been speculated to play a role in scattering around the positronium formation threshold [10,12].

This work represents an unambiguous experimental identification of Wigner cusps in positron scattering. It confirms many years of speculation that these features could exist, in particular, around the threshold for positronium formation, which is typically the most dominant scattering channel in low energy positron collisions. The present measurements for He and Ar are in reasonable qualitative agreement with those of Coleman *et al.*, with some evidence of a similar cusp feature visible in their results. Furthermore, the differences that do exist between the two results could be explained, for example, by the poorer energy resolution of their measurements combined with an energy scale difference. However, the present results for Xe are quite different from those of the same authors as we do not observe the strong upward step in the cross section through the Ore gap that they have reported.

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