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Radiative electron capture at ultrarelativistic energies: 33-TeV Pb^{82+} ions

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Cross sections for radiative electron capture (REC) by 33-TeV Pb^{82+} ions in Be and C targets have been extracted from an analysis of measurements of total electron capture by these ions in Be, C, Al, Cu, Sn, and Au targets. The REC cross sections in the Be and C targets, where REC is significant, were obtained by subtracting cross sections for electron capture from pair production (ECPP), the only other significant capture process at these energies. The ECPP contributions in Be and C were determined from extrapolations of measured cross sections in the heavier targets where the ECPP process dominates, with suitable accounting for slightly decreased screening effects for the light targets. We obtain an experimental *K*-REC cross section (0.010 ± 0.002b per electron per Pb *K* vacancy), which agrees with a calculation of REC made by applying detailed balance to the corresponding process of radiative recombination and using tabulated photoelectric effect cross sections. A comparison is also presented of the present experimental result with other heavy-ion measurements made at lower energies, and with nonrelativistic and relativistic calculations, which differ considerably in this energy regime.

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I. INTRODUCTION

At extremely high, ultrarelativistic energies, heavy ions colliding with target atoms capture electrons into bound states primarily by only two mechanisms, normal nonradiative capture being a negligibly weak process except for very heavy targets. One mechanism is radiative electron capture (REC), in which a target electron is transferred from the laboratory fixed reference frame to the ion's moving frame into a bound state of the ion. REC proceeds with the simultaneous emission of a photon, which allows for the conservation of total momentum and energy. When the ion speed (v) is sufficiently greater than that of the electron, either initially in the target or in the final ion bound state, the electron can be treated as initially free, and the REC process is equivalent to radiative recombination (RR). RR is the exact time inverse of the normal photoelectric effect. REC cross sections at high energies can thus be calculated using detailed balance and known photoelectric cross sections [1]. For high energies, all electrons are equivalent and independent, so that REC cross sections should be rather precisely proportional to the target atomic number, i.e., $\sim Z_T$. At high energies, REC cross sections scale as approximately the fifth power of the ion charge and the inverse of the ion's energy, or $\sim Z_P^5/\gamma$, where γ is the Lorentz factor, $\gamma = 1/(1-\beta^2)^{1/2}$, $\beta = v/c$, c is the velocity of light, and Z_P is the projectile atomic number.

The second electron-capture process available at ultrarelativistic energies is electron capture from pair production (ECPP). ECPP is a special case of electron-positron pair production in Coulomb collisions between the ion and an atom or ion, in which the pair electron is formed in an unoccupied, bound state of the ion. ECPP cross sections scale as approximately the square of the target charge [i.e., $\sim(Z_T^2 + Z_T)$—the linear Z_T term being added to account for Z_T independent additional target electron scattering centers when the target is a neutral atom]. For $\gamma \gtrsim 100$, ECPP cross sections are expected to increase approximately as $\sim(a + b \ln \gamma)$, where a and b are energy independent for each collision system [2]. Above $\gamma \sim 20$, ECPP exceeds REC, especially for heavy elements, because of the Z_T^2 scaling.

Measurements of REC for heavy ions have been performed at relativistic energies by a number of groups [3–6]. The highest energy measurements reported previously were carried out by Claytor *et al.* [6] at the Brookhaven alternating-gradient synchroton (AGS) accelerator facility using 10.8-GeV/nucleon ($\gamma = 12.6$) Au^{79+} beams in a variety of solid targets. The authors reported good agreement between experiment and theory, employing calculations based on tabulated photoelectric cross sections [1,8].

In a recent paper [7], we presented measurements made at the CERN SPS accelerator facility of cross sections for total electron capture and loss by 33-TeV Pb ions in a wide range of elemental solids. These data were used to extract ECPP and ionization cross sections for comparisons with several theoretical calculations [2,7–10]. In Ref. [7], our experimental total capture cross sections were corrected for REC contributions to obtain ECPP cross sections by subtracting theoretical REC values taken from the tabulations of Anholt and Becker [8]. Mokler has pointed out that the reverse procedure can be used to approximate REC cross sections; i.e., by subtracting theoretical ECPP cross sections from our total capture data [11]. For heavy targets, the REC contributions are relatively small, e.g., amounting to ~4% for Pb+Au, so that errors in REC cross sections were relatively unimportant in obtaining accurate ECPP cross sections. The experimental ECPP values extracted in this way were found to agree surprisingly well with existing theory, except for ECPPs in the

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light targets Be, C, and Al, which were found to exceed theory. Initially, target-dependent differential survival of an excess of ECPP electrons captured into excited states was invoked as a possible explanation for the large cross sections for low Z_T targets. However, REC contributions at low Z_T are significant, and we have therefore investigated more closely the possibility of obtaining relatively accurate REC cross sections from the total capture data. The results are presented here.

II. METHODS

The method used to extract REC cross sections from the total capture data is relatively straightforward; RECs for Be and C targets were obtained by subtracting fitted ECPP contributions derived from extrapolations of the heavy target data where ECPP dominates. Cross sections measured for heavy targets (Al, Cu, Sn, and Au; $Z_T \geqslant = 13$) were least-squares fitted according to the expected $(Z_T^2 + Z_T)$ scaling for ECPP, after initially correcting for REC using theoretical estimates [8]. Screening effects leading to deviation from the $(Z_T^2 + Z_T)$ scaling of the ECPP cross sections were expected to be small because relevant impact parameters for ECPP lie well within the *K*-shell radii for all targets except possibly Au. Calculations of atomic screening effects for ECPP have not yet been published. However, screening effects for free-pair production have been investigated [12]. For $Au^{79+} + Au$ at 200 GeV/nucleon, the authors find an ~5% reduction in total pair production below nucleus-nucleus results. The screening effect is only weakly Z_T dependent, being weaker for low Z_T targets. We have also previously noted extremely good Z_T^2 scaling in measurements of cross sections for the production of free electron-positron pairs in these targets [13]. To improve our fitted results, small systematic corrections potentially arising from screening variations and from the differential survival of electrons captured into excited states (i.e., variations in relative strengths of radiative stabilization to $1s$ competing with secondary ionization in solid targets) were taken into account with a weak product term linear in Z_T; a ''screening'' correction term. The initial estimates of the ECPP contributions from the fit results were then subtracted from the measured total capture cross sections for the lightest targets (Be and C—where REC is ~25–30 %) to obtain average REC cross sections per target electron. These results were then input as corrections to the total experimental cross sections in a second iteration, and the fitting process was repeated until consistent sets of REC and ECPP cross sections were obtained. This iterative process was repeated with initial start REC values lying above and below the final values, with the same outcome. If variations from strict $(Z_T^2 + Z_T)$ scaling of ECPP are completely neglected in the fitting (i.e., the screening correction term is set to unity), the REC result increases by $< 10\%$.

III. RESULTS AND DISCUSSIONS

Figure 1 shows the total cross sections from the present measurements, the fitted ECPP cross sections, and the resulting REC cross sections as functions of Z_T; all three are normalized to $(Z_T^2 + Z_T)$ for plotting purposes. For bare 33-TeV Pb^{82+} ions, the REC result averaged for Be and C is $\sigma_{\mathrm{REC}} = 0.019 \pm 0.004$ b/electron, which is ~20% larger than predicted for REC in Ref. [8]. The quoted error includes statistical and fitting uncertainties. This larger REC cross section only slightly modifies our previously published ECPP cross sections; the greatest effect being an ~20% reduction in σ_{ECPP} for Be, while σ_{ECPP} for Au is unchanged.

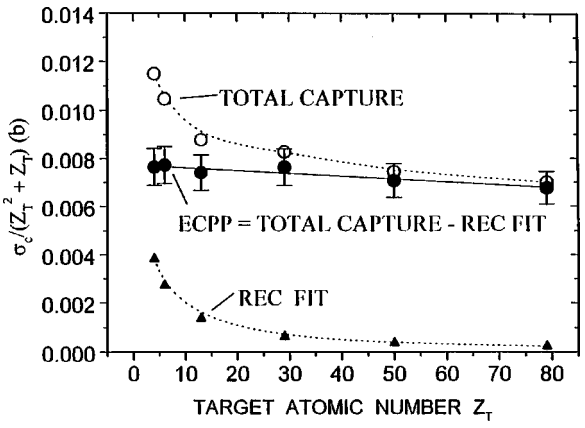

FIG. 1. Measured cross sections in barns for electron capture by 33-TeV Pb^{82+} ions in solid targets, compared with fitted contributions from ECPP and REC. The solid and dotted line curves give least-squares-fit results.

The total capture cross sections measured at the BNL AGS accelerator by Claytor *et al.* [6] for 10.8-GeV/nucleon $(\gamma = 12.6)$ Au^{79+} + C and Al (which are almost totally due to REC) give 0.30 ± 0.03 b/electron. As noted previously, REC cross sections scale asymptotically as $\sim Z_P^5/\gamma$, leading to an expected Pb^{82+} total REC cross section at $\gamma = 168$ of 0.027 b/electron from extrapolation of the AGS Au measurements. The ~40% difference between our measurement and extrapolation from $\gamma = 12.6$ may be partly explained by differences in the survival fractions of excited-state electrons in the two cases. This is because of differences in relative ionization rates and apparent radiative lifetimes due to Lorentz time dilation. At $\gamma = 168$, the apparent radiative lifetime of the $Pb^{81+}(2s)$ state is 3.04×10^{-12} sec [14], corresponding to a path length of 0.09 cm. Assuming that the ionization cross section for $Pb^{81+}(2s)$ + C is three times larger than our experimental value obtained for the ground state, i.e., 0.93 kb [7,15], the mean path length for $2s$ ionization in C is ~0.01 cm, leading to a radiative stabilization fraction of only ~10% for these ions in an equilibrium thickness target. At $\gamma = 12.6$, the corresponding fraction for survival of $Au^{78+}(2s)$ in carbon is ~90%, under the same assumptions, so that effectively all excited-state capture survives.

The Pb *K*-shell electron photoelectric cross section $\sigma_{\phi,K}$ for hydrogenlike $Pb^{81+}(1s)$ at 86 MeV (the mean target electron energy seen in the projectile rest frame) is 0.017 b/electron—as interpolated from Tables 2–7 and 3–22 of Ref. [1]. The corresponding *K*-REC cross section at $\gamma = 168$ is also 0.017 b/electron, using the relation [16]

$$\sigma_{K-\mathrm{REC}} = [((\gamma - 1) + E_{B,K})^2 \sigma_{\phi,K'} / (\gamma^2 - 1)]$$

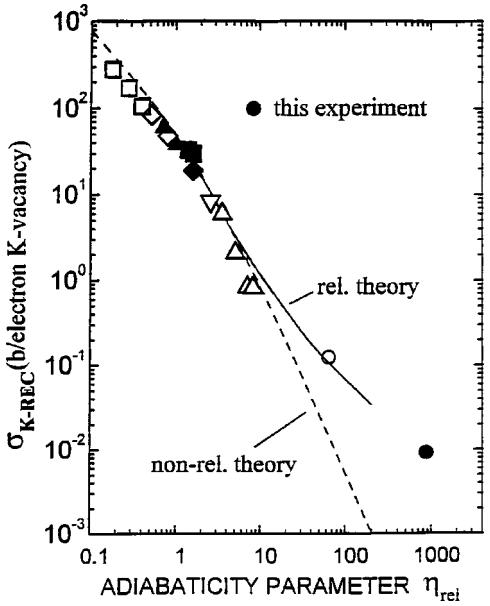

FIG. 2. Total *K*-REC cross sections per target electron, normalized to the number of *K*-shell vacancies, plotted as a function of the adiabaticity parameter η, as defined in the text. For $\eta<10$, the data are taken from Fig. 11 of Ref. [3], where these data sources are also referenced. The open symbol (○) data point is for Au at $\gamma=12.6$ ($\eta\cong 65$) from Ref. [5]. The current *K*-REC measurement for Pb at $\gamma=168$ ($\eta\cong 856$) is displayed as a solid symbol (●).

derived from detailed balance, where $E_{B,K}$ is the projectile $1s$ electron binding energy in units of the electron rest mass energy, $m_e c^2$.

As in Refs. [3] and [11], the experimental *K*-REC cross section obtained here may be compared with previous measurements and calculations for REC in other collision systems, especially at much lower energies, by plotting it as a function of an adiabaticity parameter $\eta_{\rm rel}$. A plot of the present result, along with a representative sample of other *K*-REC cross sections, is shown in Fig. 2. The parameter η, defined in Eq. (11) of Ref. [3], has been modified for plotting data in the very-high-energy regime using the relativistically correct electron kinetic energy and projectile binding energy ($E_{B,P}$) as

$$\eta_{\rm rel}=(\gamma-1)m_e c^2/E_{B,P}\,.$$

For lower energies where $\beta\ll 1$, and $\gamma\sim 1$, the two definitions yield the same value for η.

In Fig. 2, our measured REC cross sections are plotted, multiplied by 0.97 to correct for small $2s$ and higher excited-state contributions not eliminated by secondary ionization in the Be and C solid targets. The measured AGS Au cross section at $\gamma=12.6$ has been multiplied by 0.83 here to account for capture to excited states that are expected to radiatively stabilize to the Au($1s$) ground state. The dashed curve presents the predictions of the nonrelativistic dipole approximation for RR given by Stobbe [17]. We note that the higher-energy measured REC cross sections included in Fig. 2 for Au at $\gamma=12.6$ and Pb at $\gamma=168$ depart drastically from the nonrelativistic approximation, and approach the expected relativistic limiting energy behavior $\sim 1/\gamma$ [4,17]. Rigorous relativistic calculations [11,18,19] given by the solid curve, which include a substantial contribution from spin-flip (magnetic) interaction, lead to much better agreement.

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