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Electromagnetically-induced nuclear-charge pickup observed in ultra-relativistic Pb collisions

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A strong increase of inclusive nuclear-charge pickup cross sections, forming $_{83}$Bi from 158 A GeV $_{82}$Pb ions, is observed in comparison to similar measurements at 10.6 A GeV. From the dependence of these cross sections on target atomic number, this increase is attributed to the electromagnetic process of pion production by equivalent photons. The observed cross sections can be reproduced quantitatively using the recently developed RELDIS code.

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The advent of ultra-relativistic heavy-ion accelerators such as RHIC at Brookhaven and CERN-SPS at Geneva has also focussed attention on the electromagnetic processes that appear when very heavy ions with $\gamma \gtrsim 100$ collide with each other or with a fixed target with high atomic number. Theorists have pointed out for many years that very large cross sections, exceeding the geometrical cross sections of the colliding nuclei by large factors [1,2], should be observable e. g. for neutron removal from the projectiles. Experimentally, only a few publications are available up to now to verify these predictions: one experiment has addressed total disintegration cross sections [3], another measured nuclear-charge-changing cross sections from 158 A GeV ^{208}Pb projectiles with emulsion techniques [4], and in a radiochemical study 1n- and 2n-removal from a Au target induced by the same projectile was observed [5]. In all three cases, cross sections up to the order of tens of barns were observed.

All these previous experiments found evidence for electromagnetic processes in reaction channels, where either the fragment mass A and/or the fragment atomic number Z were lower than those of the incoming projectile. Those channels are by far the dominating ones due to the large number of conceivable (hadronic and electromagnetic) processes, which all lead to a *reduction* in Z and/or A (such as knock-out, sequential breakup, evaporation, etc.). In rare cases, however, the nuclear charge Z of the projectile is *increased*, a process which in the following will be called nuclear charge-pickup ($\Delta Z = +1$). Such reactions can be easily explained at low energies, below the Fermi energy in nuclei, by proton transfer through the nuclear overlap zone. At relativistic energies, however, the Fermi spheres of projectile and target are totally non-overlapping, preventing any transfer of e. g. a target proton to the projectile. Instead, we can assume Δ-resonance formation and decay in nucleon-nucleon (NN) collisions to be the most likely elementary processes in which a projectile neutron can be converted into a proton, e. g. by $n \rightarrow \Delta^0 \rightarrow p + \pi^-$ with subsequent absorption of the proton in the projectile and emission of the π^- [6].

A systematic experimental study of inclusive charge-pickup cross sections $\sigma(\Delta Z = +1)$ as a function of both, energy and target mass, for Au projectiles with energies between 1 and 10 A GeV [7] reveals a steady decrease of these cross sections with increasing energy. The dependence on target mass A_T is very weak and can be described by a power law $\sigma(\Delta Z = +1) \propto A_T^{\kappa}$ with an energy-independent exponent $\kappa = 0.223 \pm 0.005$ [7]. The measurements of Dekhissi *et al.* [4] at 158 A GeV yielded very similar results, with a slightly increased $\kappa = 0.4 \pm 0.1$. These observations suggest that the NN processes mentioned above are the most likely mechanisms, and that electromagnetic processes do not contribute even at 158 A GeV. As will be demonstrated in the following, our experimental results as well as their interpretation are drastically different.

The present experiment is primarily aimed at the study of nuclear-charge-changing cross sections in 158 A GeV ^{208}Pb projectiles induced by various target materials

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ranging from hydrogen to gold. Since only inclusive cross sections of Bi formation are measured, without detection of emitted particles, the basic reaction mechanisms (hadronic or electromagnetic) have to be inferred from their very different dependence on target nuclear charge. The key feature of the present experiment is the usage of an ionization chamber as the Z-sensitive detector. Compared to nuclear-track detectors [4], the small areal density of the ionization chamber induces much less secondary reactions, and consequently requires an almost negligible correction of the data. In addition, much better statistics is obtained than in the track-detector experiment [4]. In this paper, the formation cross sections of $_{83}$Bi ions are reported; results for total and partial nuclear-charge-changing cross sections will be reported elsewhere [8].

The experiment was carried out at the H2-beamline in the North Hall of the CERN SPS accelerator facilities. The experimental setup consisted of a scintillator detector and two Z-sensitive MUltiple Sampling Ionization Chambers (MUSICs) [9], between which the reaction targets were mounted. With the first MUSIC (in front of the targets) the incoming Pb ions were counted, whereas the second MUSIC (behind the targets) registered the atomic numbers of the outgoing reaction products. The entire setup was about 2 m long and was placed in air between two vacuum windows of the beam pipe.

The scintillator detector consisted of 100 μm thick BC418 material with a diameter of 20 mm and delivered a fast trigger signal for each incoming ion. The MUSICs had active volumes of 36 cm length (in beam direction) and areas of 20×20 cm^2 (perpendicular to the beam axis). They were operated with P10 gas (90 % argon, 10 % methane) at normal temperature and pressure and had four-fold segmented anodes. The energy signals, which are proportional to the atomic numbers of the penetrating ions, were recorded event-by-event. The timing outputs were used to determine the horizontal positions of the ions. In the off-line analysis this position information was used to suppress scattered ions (approximately 1 %), which did not hit the targets. The energy signals of each MUSIC yielded the nuclear-charge spectra, from which the charge-changing cross sections were derived. The charge resolution amounts to 0.3 charge units (standard deviation). The high-Z parts of such spectra are shown in Fig. 1.

The targets had diameters of 45 mm and were mounted on a remotely controlled, horizontally movable ladder placed between the two MUSICs. One polyethylene (CH_2) target and three targets of each of the following elements were used: carbon, aluminum, copper, tin, and gold. Their thicknesses covered areal weights ranging from 0.3 g/cm^2 to 6 g/cm^2 corresponding to total nuclear-interaction probabilities of approximately 5 %, 10 %, and 20 %.

The beam was extracted at a kinetic energy of 158 A GeV, had a spill length of 5 seconds, a horizontal width of 3 mm (standard deviation), and an angular divergence of 50 μrad (standard deviation). The intensity of the incident beam was varied during the measurements between 300 ions per second and 10^4 ions per second depending on the needs of another experiment running simultaneously at the same beamline [10].

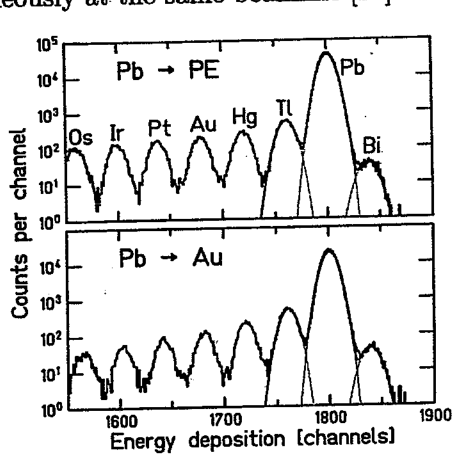

FIG. 1. High-energy part of energy-deposition spectra of the second MUSIC downstream from a 0.5 g/cm^2 polyethylene target (upper part) and a 3 g/cm^2 gold target (lower part). Gaussian fits to the Tl, Pb, and Bi peaks and their sums are shown.

For the different target materials, between $3 \cdot 10^5$ and $1.1 \cdot 10^6$ incoming Pb ions and between 300 and 1300 outgoing Bi ions were recorded in the different runs. The measured spectra were fitted with a sum of Gaussian peaks, which are, as a fit result, characterized by almost equal width and spacing. The number of Bi ions was determined from the area of the corresponding Gaussian. The smaller charge-pickup probability in lighter target materials was compensated by higher total numbers of counts. This allows a clear identification and a proper determination of the Bi peak areas even for the lightest target materials, although the Bi peak is about three orders of magnitude smaller than the Pb peak (see figure 1). Because the nuclear charge-pickup probability is much smaller than unity in the targets used, the cross sections can simply be determined from $\sigma(\Delta Z = +1) = (R_1 - R_0)/(nd)$, where nd is the number of target atoms per unit area and R_1 and R_0 are the ratios of detected Bi ions (in the second MUSIC) to incoming Pb ions (counted in the first MUSIC) with and without target, respectively. The pickup cross section for hydrogen is calculated from the measured cross sections for polyethylene and carbon according to $\sigma_H = 0.5 \cdot (\sigma_{CH_2} - \sigma_C)$.

For all target materials investigated, the cross sections determined for the different thicknesses agree with each other within the experimental errors (i. e. no systematic thickness dependence is observed) and are therefore averaged to obtain the final values given in Table I. The errors are governed by the statistical uncertainties of the Bi counts. Minor contributions arise from target thickness fluctuations (about 0.5 % contribution) and the empty-target-correction R_0 (about 1 % contribution). Because of the low rate of incoming ions and signal decay times of a few μs the probability for pile up of the energy signals is several orders of magnitude smaller than the observed charge-pickup probability.

The experimental results are presented in the last column of Table I and visualized in Fig. 2. There is a marked increase in $\sigma(\Delta Z = +1)$ with the target atomic

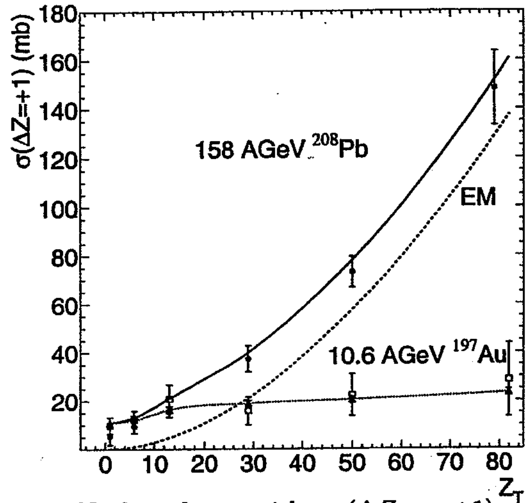

FIG. 2. Nuclear-charge pickup ($\Delta Z = +1$) cross sections as a function of target atomic number Z_T. The present data (158 A GeV Pb) are shown by full circles. The solid curve is the sum of the electromagnetic contribution (EM, dashed line) and the nuclear contribution to the $\Delta Z = +1$ cross section. For comparison, data obtained with 10.6 A GeV Au-ions [11,12] are depicted with open symbols (triangles and squares) which are connected by the dotted line to guide the eye.

TABLE I. Experimental nuclear-charge-pickup cross sections, $\sigma_{\rm exp}$, in mb at 158 A GeV from this work, and at 10.6 A GeV from Ref. [12]. Electromagnetic contributions, $\sigma_{\rm EM}$, are calculated to be substantial in this work, but negligible for 10.6 A GeV. Total calculated cross sections for 158 A GeV, $\sigma_{\rm tot}$, have therefore been obtained by adding $\sigma_{\rm exp}$ from Ref. [12] to our electromagnetic contribution $\sigma_{\rm EM}$.

	10.6 A GeV ^{197}Au		158 A GeV ^{208}Pb		
	$\sigma_{\rm EM}$	$\sigma_{\rm exp}$	$\sigma_{\rm EM}$	$\sigma_{\rm tot}$	$\sigma_{\rm exp}$
Target	this work	Ref. [12]	this work		this work
H	0.001	10.9±0.7	0.03	10.9	$5.4^{+1.9}_{-3.6}$
C	0.011	12.1±0.7	1.01	13.1	9.4±2.8
Al	0.021	16.3±1.0	4.74	21.0	15.4±2.3
Cu	0.017	18.9±1.1	21.03	39.9	37.4±5.4
Sn	0.0	20.4±1.4	57.54	77.9	73.2±6.4
Au	0.0	–	127.87	151.1*	148±15
Pb	0.0	23.2±1.4	137.42	160.6	–

*For the nuclear contribution the experimental cross section for the lead target was used.

number Z_T. For the high-Z_T target materials the measured cross sections are almost one order of magnitude larger than for 10.6 A GeV Au-ions [11,12]. To a good approximation the cross sections are proportional to Z_T^2, indicating a significant contribution from electromagnetic processes. In marked contrast, the pickup cross sections measured for Au at the energy of 10.6 A GeV are almost independent of Z_T, a clear indication of their purely hadronic origin. This implies a very weak energy dependence and one can use these results as an estimate of the *nuclear* contributions to our measured data. The origin of the electromagnetic contribution will be described in the following.

At ultra-relativistic energies ($\gamma \gtrsim 100$), a new mechanism of nuclear-charge-changing interactions between heavy ions comes into play because the maximum equivalent photon energy exceeds the pion production threshold [13]. The maximum equivalent photon energy is estimated as $E_{\rm max} = \gamma\hbar c/b_c$, where b_c is the minimum impact parameter in electromagnetic interactions [1,2]. In collisions of 158 A GeV Pb ions $E_{\rm max}$ amounts to 4.1 GeV for Pb+H and to 2.2 GeV for Pb+Au. These values are much larger than the pion production threshold of $E_{th} \simeq 140$ MeV. If a π^- is produced in the reaction $\gamma n \to \pi^- p$, it may be emitted while the associated proton may be captured to form a Bi residual nucleus. In general, this Bi nucleus is highly excited. In most cases, however, deexcitation involves only neutron evaporation (within a typical time scale of the order of $10^{-20}\ldots10^{-18}$s), a process which is much faster than the time between the collision and the detection as the final Bi nucleus (approximately 3 ns, corresponding to approximately 500 ns in the rest frame of the nucleus). The photonuclear reactions $(\gamma, \pi^- xn)$, $x = 0\ldots9$, induced by *real* Bremsstrahlung photons, were studied many years ago and the reader is referred to a recent paper where such reactions are studied by radiochemical methods [14]. The same reactions, induced by *equivalent* photons, are possible in ultra-relativistic heavy-ion collisions.

To describe the electromagnetic component of charge-changing interactions leading to $\Delta Z = +1$ the Relativistic ELectromagnetic DISsociation model is used, which is described in Ref. [2] and implemented as the RELDIS code. In this model, the initial γN interaction induced by an equivalent photon initiates a cascade of successive quasi-free hadron-nucleon collisions in the nuclear medium. In addition to the initial $\gamma N \to \pi N$ reaction, the channels of multiple pion production are taken into account. At the end of the hadronic cascade, when the last fast particle leaves the nucleus, an excited residual nucleus is left over which mainly decays via neutron evaporation.

Having determined the probability for an increase of the nuclear charge, the cross section for the electromagnetic charge pickup can be estimated by means of the Weizsäcker-Williams method [1,2]. Double photon absorption processes are taken into account by applying the harmonic-oscillator ansatz in conjunction with the folding model [15]. The resulting cross sections are listed in column 2 of Table I for 10.6 A GeV Au ions and in column 4 for 158 A GeV Pb ions.

The electromagnetic contributions $\sigma_{\rm EM}$ to the charge-pickup cross sections for 10.6 A GeV Au ions are almost negligible or even non-existent for high-Z targets (see column 2 of Table I), because the highest possible equivalent photon energy is smaller than the pion-production threshold. The situation is drastically different at 158 A GeV, where a substantial part of the virtual photon spectrum exceeds this threshold. This is clearly seen in Fig. 3, where the product of $\sigma_{A_P}(E_\gamma)N(E_\gamma)$ is shown for the two different projectiles and energies. Here, $\sigma_{A_P}(E_\gamma)$ is the total photoabsorption cross section for the projectile nucleus A_P and $N(E_\gamma)$ is the spectrum of virtual photons.

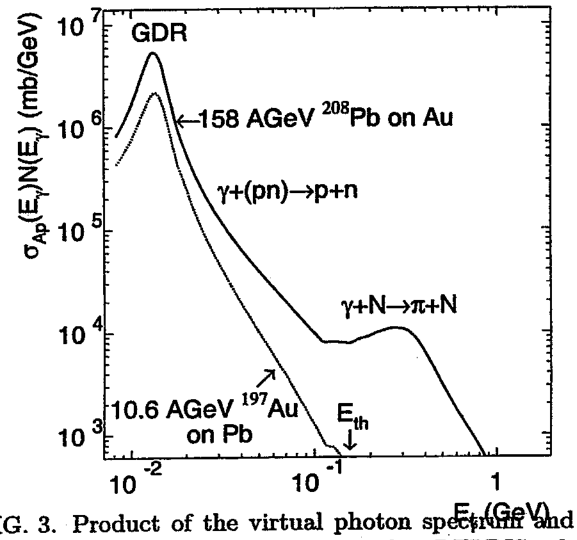

FIG. 3. Product of the virtual photon spectrum and the total photoabsorption cross section used in RELDIS calculations for 10.6 A GeV Au ions and for 158 A GeV Pb ions. The threshold energy for the $\gamma n \rightarrow \pi^- p$ process, E_{th}, is indicated by the vertical arrow next to the energy axis.

One can clearly see that the absorption of virtual photons via Giant Dipole Resonance (GDR) excitation and quasideuteron absorption dominate in both cases, but that, in addition, photon absorption in the Δ-resonance region becomes important for the higher beam energy. The electromagnetically-induced charge pickup originates exclusively from this part of the spectrum.

For a quantitative comparison with the experimental data we assume that the nuclear contribution for 158 A GeV Pb ions is identical with the charge-pickup cross section measured for 10.6 A GeV Au ions [12] (the data of Ref. [11] are not used because of their much larger uncertainties). Thus, adding the values given in columns 3 and 4 of Table I, we obtain the total charge-pickup cross sections $\sigma_{\rm tot}$ listed in column 5 and visualized by the full line in Fig. 2. In particular for high Z_T, the results of the RELDIS calculation are in excellent agreement with the measured data. It should be noted, that pure π and ρ exchange as described in [16] seems not to be sufficient to describe the experimental findings.

In summary, the nuclear-charge pickup ($\Delta Z = +1$) of 158 A GeV Pb ions has been investigated. In contrast to earlier studies at 10.6 A GeV, we observe a strong, almost quadratic increase of the cross sections with target atomic number Z_T. Our experimental findings can be described quantitatively with RELDIS calculations showing that in collisions with high-Z nuclei the dominant contribution to nuclear-charge pickup is due to electromagnetic processes of π^- production by virtual photons. This contribution is completely negligible at AGS energies and is observed for the first time in the present experiment at the SPS. To the best of our knowledge, this is the first indication of meson production by virtual photons in heavy ion collisions. Together with electron capture from e^+e^- pair production and electromagnetic heavy ion dissociation, this will contribute to beam loss and localized beampipe heating in ultra-relativistic heavy ion colliders [17].

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