ELECTROMAGNETIC DISSOCIATION OF RELATIVISTIC HEAVY IONS

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Electromagnetic Dissociation (ED) occurs in collisions of relativistic heavy ions where the impact parameter is larger than the interaction radius. In ED collisions, absorption of a virtual photon generally leads to the excitation of a nuclear giant resonance. The NA53 experiment studies ED by bombardment of Au targets with 40 and 158 GeV/nucleon ^{208}Pb projectiles from the CERN-SPS accelerator. Preliminary $\sigma_{\rm ED}$ results for the one- and two-neutron removal processes are reported for 158 GeV/nucleon beams. Theoretical predictions for $\sigma_{\rm ED}$ including the effects of both E1 and E2 giant resonances were calculated and extended to energies for heavy ion collisions at the RHIC and LHC colliders.

Introduction

Studies of relativistic heavy ion collisions emphasize the study of hadronic interactions at small impact parameters but at energies for heavy nuclei at RHIC and those planned for the LHC, most of the reaction cross section will result from non-hadronic processes due to electromagnetic interactions. Electromagnetic Dissociation (ED) is such a process involving a purely electromagnetic interaction for impact parameters greater than the strong interaction radius.

An example of an ED interaction is shown in Fig. 1 where a Au nucleus is excited by the passage of a relativistic Pb projectile and decays by the emission of one neutron. The ED process can be visualized as the absorption of one or more photons by the nucleus due to the very strong electromagnetic fields generated. This usually leads to the excitation in the nucleus of a giant multipole resonance. The giant resonance usually decays by the emission of one or more neutrons since charged particle emission for heavy nuclei is retarded by the Coulomb barrier.

ED was first observed by Heckman and Lindstrom [1] in projectile fragmentation and in target fragmentation of Au and Co by our group [2]. Later the ED measurements were extended to La projectiles [3] and two-neutron removal processes [4]. Large $\sigma_{\rm ED}$ were observed with Au beams [5] using the SIS accelerator at GSI.

In this paper, we report preliminary values for $\sigma_{\rm ED}$ for the one- and two-neutron removal processes obtained from the collision of Pb projectiles with Au targets at the SPS accelerator at CERN. Below we describe the experiment and calculations of $\sigma_{\rm ED}$. A comparison between the measured and calculated values is given and the calculations are extended to energies for Au beams in the RHIC and LHC colliders.

1. Experimental Method

The NA53 experiment was carried out by bombarding Au targets of thickness 0.005 mm with 40 and 158 GeV/nucleon beams from the SPS accelerator. The bombardments were carried out in the NA50 beamline about 30 m upstream from the NA50 target but just downstream from the NA50 hodoscope. The layout for the NA53 experiment is shown in Fig. 2. Signals from the NA50 hodoscope were used to determine the total number of Pb ions incident on the Au targets. Beam

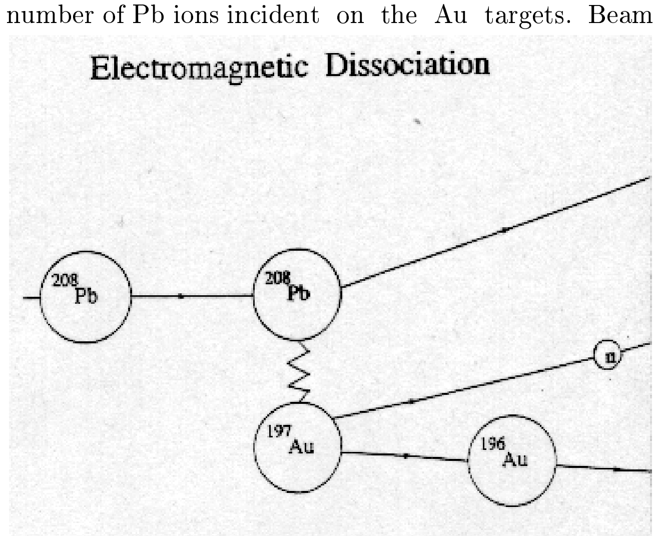

Fig. 1. Schematic diagram of a collision of a Pb projectile with a Au target leading to ED of the Au with emission of a single neutron

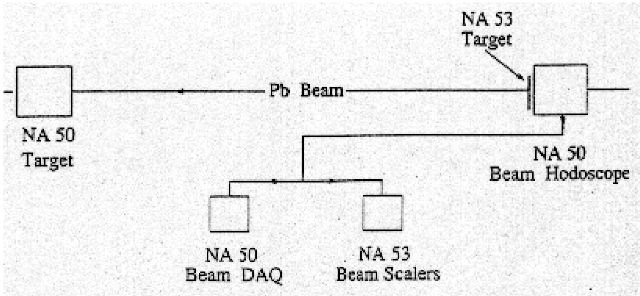

Fig. 2. The layout for the Na53 target and beam scalers in the NA50 beamline

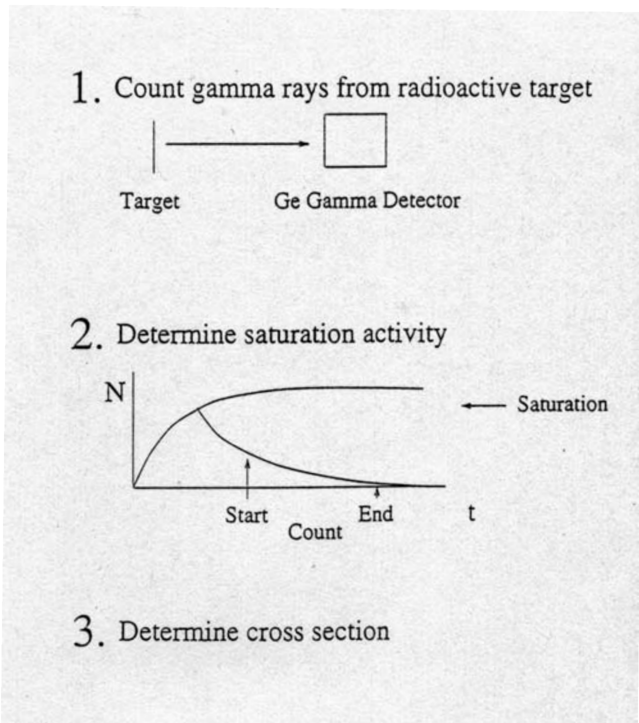

Fig. 3. The steps necessary to determine the saturated activities generated by the one- and two-neutron removal processes from bombardment of the Au targets

intensities were typically 4×10^7 per spill and total fluences on the targets were of the order of 4×10^{10} projectiles.

1.1. Determination of Neutron-removal Cross Sections

The cross sections for the one- and two-neutron removal processes were determined by measuring the saturated activities of ^{196}Au and ^{195}Au, respectively. Since the halflives of the two above nuclides were 6.2 and 183

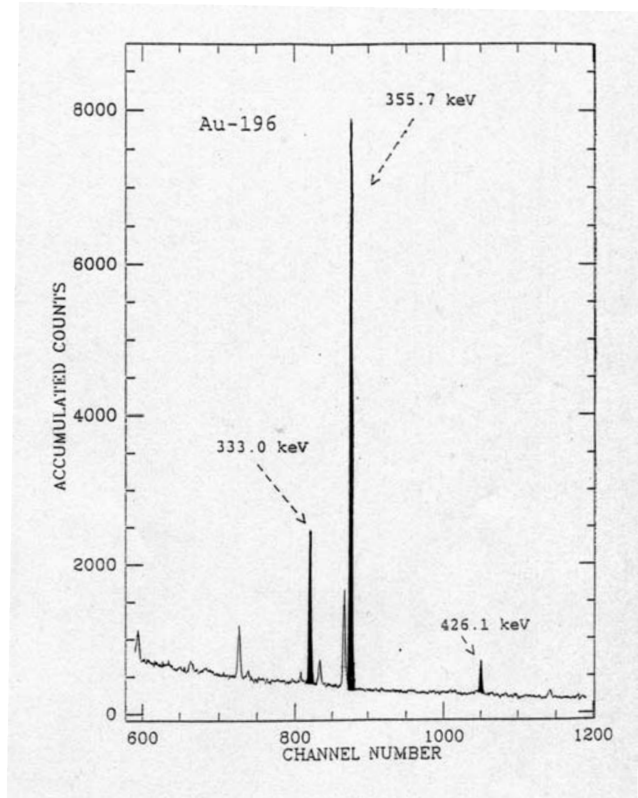

Fig. 4. A portion of a typical ^{196}Au spectrum from a Au target bombarded at the SPS. Three prominent γ rays from ^{196}Au decay are indicated

days, respectively, the targets were shipped to Iowa for γ counting and determination of the saturated activity. The three steps in this process are demonstrated in Fig. 3.

In each case, the γ decay was followed for several halflives. A typical spectrum for ^{196}Au is shown in Fig. 4 where the ^{196}Au γ rays are quite prominent.

Once the saturation activities had been measured by counting of the 356-keV γ ray from ^{196}Au and the 93-keV γ ray from ^{195}Au, a number of corrections were necessary before the final cross sections could be determined. The experimental cross sections were determined from the expression

$$\sigma(\mathrm{cm}^2) = \frac{N(\mathrm{atoms/sec})M(\mathrm{g/mole})}{f(\mathrm{proj/sec})N_a(\mathrm{atoms/mole})\rho(\mathrm{g/cm}^2)}. \qquad (1)$$

The disintegration rate at saturation was determined from the γ-ray count rate by

$$N(\mathrm{atoms/sec}) = \frac{n(\mathrm{counts/sec})}{bGB\lambda\epsilon}, \qquad (2)$$

where n refers to the counts per second at saturation and ϵ, b, G and B represent absolute detector efficiency, γ-ray branching ratio, γ-ray absorption in the target and correction for finite beam width, respectively. λ is the radioactive decay constant in $\sec^{-1}$.

1.2. Nuclear Contribution to Neutron-removal Cross Sections

To estimate the nuclear contribution, we use the concepts of factorization [6] and limiting fragmentation [7] of the nuclear cross section. Factorization assumes

$$\sigma_{TP}^{F} = \gamma_T^F \gamma_P^T,$$

where F, T, and P indicate dependences on target fragment, target and projectile, respectively. Limiting fragmentation states that for sufficiently high energies, the cross section for the production of fragment F_i is independent of energy.

We estimate the nuclear part of the neutron removal reaction from ratios such as

$$\frac{\sigma[^{197}\mathrm{Au}(^{208}\mathrm{Pb},\mathrm{X})F_i]}{\sigma[^{197}\mathrm{Au}(\mathrm{p},\mathrm{X})F_i]} \qquad (3)$$

The proton cross sections were measured using the 28-GeV beam from the AGS accelerator. Assuming, for example, factorization for the nuclear part of the ^{197}Au(^{208}Pb, X)^{196}Au cross section,

$$\sigma_{\mathrm{nucl}}(^{208}\mathrm{Pb},^{196}\mathrm{Au}) = \sigma(\mathrm{p},^{196}\mathrm{Au})\frac{\sigma(^{208}\mathrm{Pb},F_i)}{\sigma(\mathrm{p},F_i)} \qquad (4)$$

Fig. 5 shows a typical set of data used to determine the nuclear contribution to a one-neutron removal cross section measured in the past.

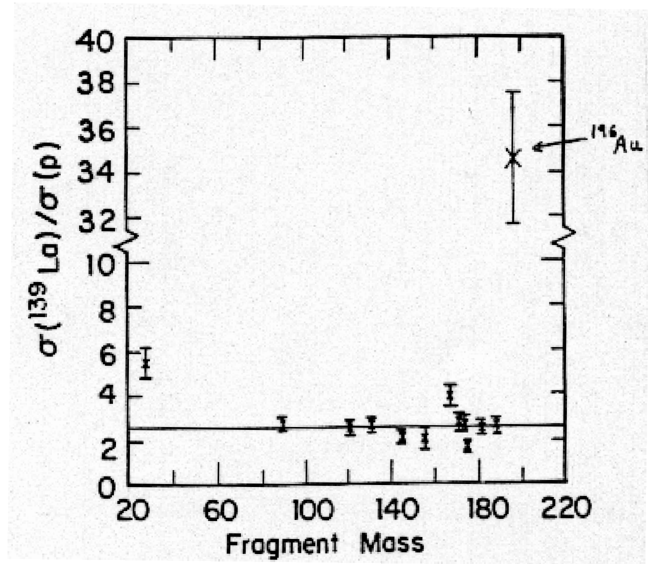

Fig. 5. An example of the experimentally determined ratio used in earlier experiments to determine the nuclear contribution to the ^{197}Au(^{139}La, X)^{196}Au cross section. The horizontal line indicates an average of the plotted ratios and is extended to indicate the nuclear contribution to the one-neutron removal process. Note that when σ_{ED} becomes large the nuclear correction is very small

2. Calculation of Electromagnetic Dissociation Cross Sections

The σ_{ED} was calculated by folding together the appropriate virtual photon spectrum with an experimentally measured photonuclear cross section. The product is then integrated as shown below to give

$$\sigma_{\mathrm{ED}} = \int N_\gamma(E_\gamma)\sigma_\gamma(E_\gamma)dE_\gamma. \qquad (5)$$

The virtual photon spectrum $N_\gamma(E_\gamma)$ was calculated using the Weizsacker—Williams (WW) method [8] in a computer program modified by Cook [9]. The term $\sigma_\gamma(E_\gamma)$ is the experimentally measured photonuclear cross section. The photonuclear cross sections for the ^{197}Au(γ, n)^{196}Au and ^{197}Au(γ, 2n)^{195}Au reactions used were those given by Veyssiere et al. [10] but multiplied by a factor of 0.93 to conform to recent measurements by Berman et al. [11]. The only adjustable parameter in the calculation is the minimum impact parameter $b_{\min}$. We have used the form $b_{\min} = r_0[A_p^{1/3} + A_t^{1/3} - X(A_p^{-1/3} + A_t^{-1/3})]$ suggested by Vary [12] where the A's refer to projectile and target, respectively. The values used for r_0 and X were 1.34 fm and 0.75, respectively. $b_{\min}$ can be visualized as a radius characterizing the range of the short-range nuclear force.

The procedure used to calculate σ_{ED} is shown in Fig. 6 where the darkened areas represent information necessary to calculate the two-neutron removal cross section.

In the past, many ED treatments have neglected the effects of transitions other than E1, but Goldberg [13] has pointed out that, for virtual photon spectra with heavy ions, the contribution to ED from M1 transitions is expected to be negligible but that contributions from E2 transitions are important since the strength of the virtual E2 spectrum for $\gamma = 3$ is about a factor of 3 greater than that for the E1 spectrum. We have used a procedure by Norbury [14] to correct for effects of E2 transitions. The parameter for the E2 giant resonance was obtained from the compilation of Bertrand [15].

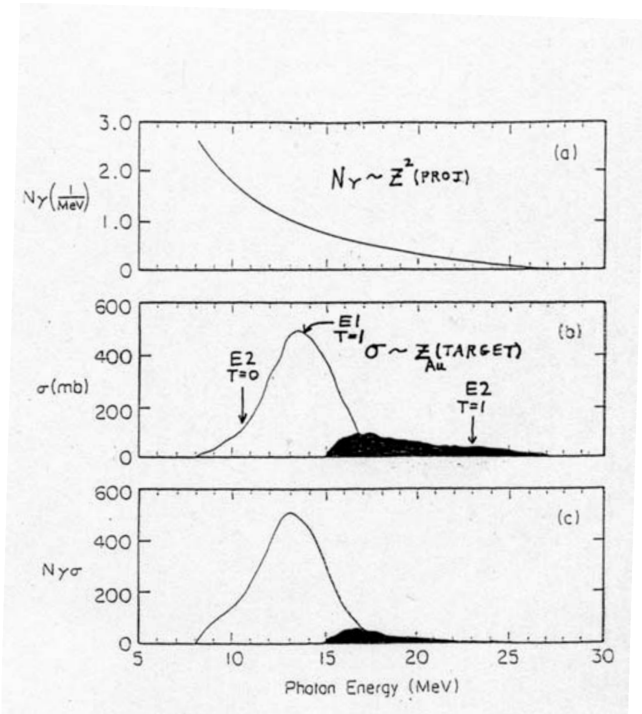

Fig. 6. Components necessary for calculation of $\sigma_{\rm ED}$ for one- and two-neutron removal processes. In this illustrative example, the virtual photon spectrum in (a) is that for 1.26 GeV/nucleon ^{139}La projectiles. Part (b) shows the ^{197}Au$(\gamma,{\rm n})^{196}$Au and ^{197}Au$(\gamma,2{\rm n})^{195}$Au(shaded) photonuclear cross sections. Part (c) shows the product of (a) and (b) that is integrated over photon energy to obtain $\sigma_{\rm ED}$

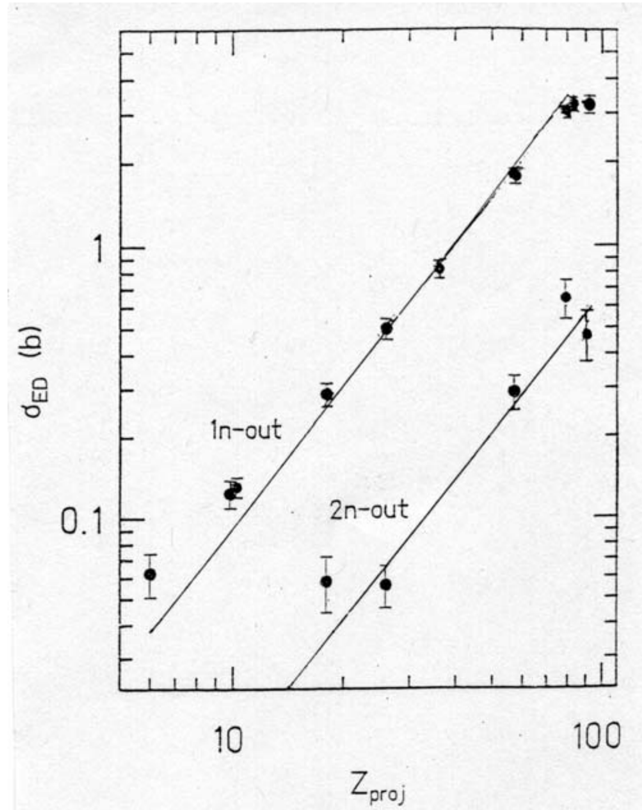

Fig. 7. $\sigma_{\rm ED}$ for one- and two-neutron removal from a ^{197}Au target as a function of projectile energy. The curves are obtained from a WW calculation taking into account excitation of both the $E1$ and $E2$ giant resonances. The data have been scaled to the same projectile energy of 1 GeV/nucleon

3. Results of Cross Section Measurements

Earlier measurements on the ED of Au targets were carried out at the Bevalac [2, 3, 4] and SIS [5]. Projectiles ranged in mass from ^{12}C to ^{207}Bi and in energies from 2 to 1 GeV/nucleon, respectively. Results for one- and two-neutron removal reactions are shown as a function of projectile charge in Fig. 7.

As can be seen from Fig. 7, the measured $\sigma_{\rm ED}$s follow a power law dependence and are generally in good agreement with the WW calculation when the effects of both the E1 and E2 giant resonances are included. For a point source interaction, $\sigma_{\rm ED}$ would be proportional to Z^2 where Z is the charge of the projectile. The WW calculation shows $\sigma_{\rm ED}$ proportional to $Z^{1.8}$. This is due to the fact that the cutoff radius $b_{\rm min}$ increases as the Z and radius of the projectile increase. As can be seen from Fig. 7, the experimental data are in good agreement with the WW calculation but show a power law dependence on Z with a power slightly less than 1.8.

It is also of interest to determine experimentally the behavior of $\sigma_{\rm ED}$ as a function of projectile energy. This is of particular interest since ED is one of the major factors determining the lifetime of heavy beams in colliders such as RHIC and the LHC. Therefore a series of experiments with Au projectiles on Au targets were carried out at the SIS accelerator [5] and the AGS accelerator at Brookhaven [16] at energies of 1.0 and 9.9 GeV/nucleon, respectively. In order to extend the measurements to even higher energies, experiment NA53 was carried out at the SPS accelerator to measure $\sigma_{\rm ED}$ for Au targets with 40- and 158-GeV/nucleon ^{208}Pb beams. PRELIMINARY values for the $\sigma_{\rm ED}$ cross sections at 158 GeV/nucleon were measured to be 26.4 ± 4.0b and 4.6 ± 0.7b for the one- and two-neutron removal processes, respectively. The corresponding "nuclear" cross sections for the above processes were determined to be 0.3 ± 0.1b and 0.13 ± 0.04b, respectively. The data at the projectile energy of 40 GeV/nucleon are being analyzed.

The PRELIMINARY results of measurements of $\sigma_{\rm ED}$ for Au targets bombarded with high energy Au and Pb projectiles are shown in Fig. 8. A logarithmic dependence of $\sigma_{\rm ED}$ on the projectile energy is expected from the WW calculations. The agreement of the data with theoretical predictions is reasonable but the predictions are systematically too high for the one-neutron removal process and systematically too low for the two-neutron removal process. Llope and Braun—Munzinger [17] have suggested that it is possible to excite a multiphonon giant E1 resonance by absorption of more than one photon. This effect has been used [5] to partially explain the enhancement of the two- and three-neutron removal processes for 1 GeV/nucleon Au projectiles on Au targets.

4. Extrapolation of Results to Collider Energies

Due to the large values of $\sigma_{\rm ED}$ for heavy projectiles at ultrarelativistic energies, ED is a major determinant of the lifetime and quality of Au beams at RHIC and will be even more significant for Pb beams at the LHC. The calculations for one- and two-neutron removal processes for Au beams on Au targets have been extended to 100 GeV/nucleon beams in the RHIC collider as shown in Fig. 8. The calculated $\sigma_{\rm ED}$s are about 49 and 7 barns, respectively. A similar calculation has been carried out for the maximum energies of Pb beams expected for the LHC collider. The results for $\sigma_{\rm ED}$ are 92 and 17 barns for the one- and two-neutron removal processes, respectively.

It is worth noting here that, at ultrarelativistic energies, a second process in addition to ED leading to neutron removal has a significant effect on the lifetimes of collider beams at RHIC and the LHC. This involves electromagnetic interactions leading to the formation of an e^+—e^- pair. The cross section for the emission of electrons is very large but the electrons are of low energy compared to the beam energies of colliders and are thus not a problem. There is a process whereby the electron from the e^+—e^- pair can be recaptured by the projectile thus changing its charge so that it is lost to the stored beam. It is calculated that this cross section is of the same order of magnitude as $\sigma_{\rm ED}$ for neutron emission but slightly larger.

Conclusions

The main conclusions from this work are listed below:

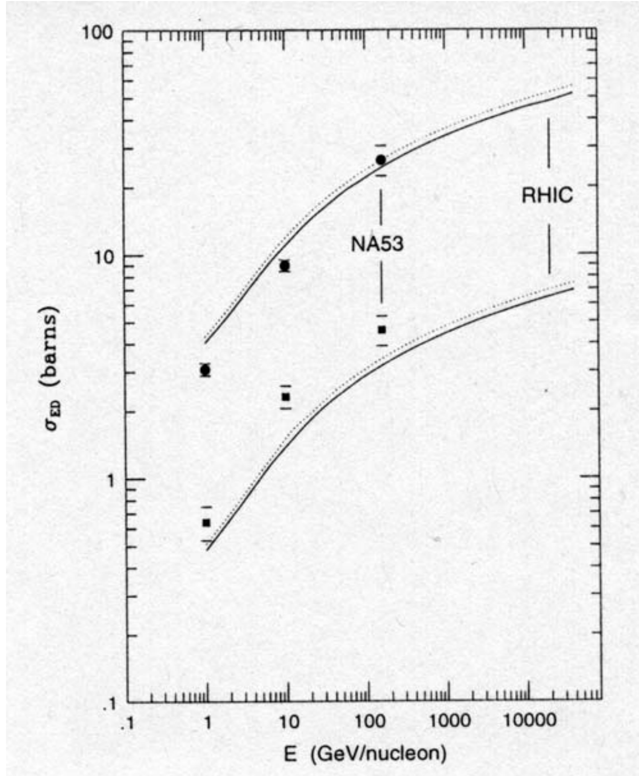

Fig. 8. Calculated $\sigma_{\rm ED}$ for Au targets. The upper and lower curves are for one- and two-neutron removal reactions, respectively. The solid and dashed curves represent the results of WW calculations for Au and Pb projectiles, respectively

1. Large ED cross sections up to 26 barns have been measured for the one-neutron removal process.

2. The ED cross section for the two-neutron removal process is typically a factor of about 7 smaller.

3. The measured ED cross section is fairly well described by:

   (a) "nuclear" cross section determined by factorization

   (b) "electromagnetic" cross section determined by folding a Weizsacker-Williams virtual photon spectrum with an experimental photonuclear cross section

4. Effects of both $E1$ and $E2$ giant resonances need to be included.

5. The one-neutron removal ED cross section extrapolates to about 50 barns for Au + Au at RHIC.

6. Neutron removal by ED and e^+—e^- pair production followed by electron recapture by the projectile are the largest constraints on lifetimes of heavy beams at RHIC and the LHC.

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ЕЛЕКТРОМАГНІТНА ДИСОЦІАЦІЯ РЕЛЯТИВІСТСЬКИХ ВАЖКИХ ІОНІВ

Дж. Хілл (від NA53-колаборації)

Р е з ю м е

Електромагнітна дисоціація (ЕД) відбувається в зіткненнях релятивістських важких іонів, коли параметр зіткнення є більшим за радіус взаємодії. ЕД в зіткненнях з поглинанням віртуального фотона приводить, в загальному випадку, до збудження гігантського ядерного резонансу. NA53-експеримент вивчає ЕД шляхом бомбардування мишеней Au ядрами ^{208}Pb з енергією 40 і 158 ГеВ/нуклон на SPS прискорювачі в ЦЕРНі. Представлено попередні результати перерізів σ_{ED} для процесів з вибиванням одного та двох нейтронів на пучках з енергією 158 ГеВ/нуклон. Теоретичні передбачення для σ_{ED}, включаючи ефекти як $E1$, так і $E2$ гігантського резонансу, були обчислені та розширені до енергій зіткнення важких іонів на прикорювачах RHIC та LHC.

ЭЛЕКТРОМАГНИТНАЯ ДИССОЦИАЦИЯ РЕЛЯТИВИСТСКИХ ТЯЖЕЛЫХ ИОНОВ

Дж. Хилл (от NA53-коллаборации)

Р е з ю м е

Электромагнитная диссоциация (ЭД) происходит в соударениях релятивистских тяжелых ионов, когда параметр соударения больше, чем радиус взаимодействия. ЭД в соударениях с поглощением виртуального фотона приводит, в общем случае, к возбуждению гигантского ядерного резонанса. NA53-эксперимент изучает ЭД путем бомбардировки мишеней Au ядрами ^{208}Pb с энергией 40 и 158 ГэВ/нуклон на SPS ускорителе в ЦЕРНе. Представлены предварительные результаты сечений σ_{ED} для процессов с выбиванием одного и двух нейтронов на пучках с энергией 158 ГэВ/нуклон. Теоретические предсказания для σ_{ED}, включающие эффекты как $E1$, так и $E2$ гигантского резонанса, были вычислены и распространены до энергий соударения тяжелых ионов на ускорителях RHIC и LHC.