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Deuteron photodissociation in ultraperipheral relativistic heavy-ion on deuteron collisions

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In ultraperipheral relativistic deuteron on heavy-ion collisions, a photon emitted from the heavy nucleus may dissociate the deuterium ion. We find deuterium breakup cross sections of 1.38 b for deuterium-gold collisions at a center of mass energy of 200 GeV per nucleon, as studied at the Relativistic Heavy Ion Collider, and 2.49 b for deuterium-lead collisions at a center-of-mass energy of 6.2 TeV, as proposed for the Large Hadron Collider (LHC). This cross section includes an energy-independent 140-mb contribution from the hadronic diffractive dissociation. At the LHC, the cross section is as large as that of hadronic interactions. The estimated error is 5%. Deuteron dissociation could be used as a luminosity monitor and a "tag" for moderate impact-parameter collisions.

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Deuterium–heavy-ion collisions are of considerable interest at heavy-ion colliders. Technically, they are much easier than proton-ion collisions because the deuteron charge-to-mass ratio Z/A is similar to that of heavy ions, greatly simplifying the magnetic optics around the collision point. Further, at the Large Hadron Collider (LHC), the matching Z/A of the two beams means that the nucleon-nucleon center-of-mass frame is closer to the lab frame than it would be in pA collisions. The similarity in proton-neutron ratios will also simplify the comparison of the data from dA and AA collisions. For these reasons, dA collisions may be preferred over pA.

Ultraperipheral dA collisions are also of interest. The strong electromagnetic field of the heavy ion acts as an intense photon beam, which strikes the deuterium, producing very high-energy γd collisions. In AA collisions, there is a twofold ambiguity over which ion emitted the photon. However, in dA collisions, the photon almost always comes from the heavy ion, allowing a clean determination of the photon energy based on the final state rapidity.

Some ultraperipheral reactions are unique to dA collisions. Here, we consider one example, photodissociation of deuterium. This reaction has a very large cross section and can serve as a luminosity monitor and as a "tag" for moderate impact parameter ultraperipheral collisions. The photodissociation cross section is

$$\sigma_{\rm diss}=\int dk\frac{dN}{dk}\sigma_d(k), \tag{1}$$

where $dN(k)/dk$ is the photon flux from the heavy ion and $\sigma_d(k)$ is the photon-deuteron breakup cross section.

The photon flux emitted by the heavy ion is obtained from the Weizsacker-Williams approach. The flux, integrated over impact parameters, b, greater than $R_{\rm min}$ is [1]

$$\frac{dN}{dk}=\frac{2Z^2\alpha}{\pi k}\left[xK_0(x)K_1(x)-\frac{x^2}{2}[K_1^2(x)-K_0^2(x)]\right], \tag{2}$$

where α is the fine structure constant, K_0 and K_1 are modified Bessel functions, and $x=kR_{\rm min}/\hbar c\Gamma$. Here $\Gamma=2\gamma^2-1$, where γ is the Lorentz boost of a single beam. The minimum radius $R_{\rm min}=R_A+R_d$ is required to eliminate the collisions that include hadronic interactions. We take 2.1 fm for the deuteron radius [2] and assume $R_A=1.2A^{1/3}$ for the heavy ion. Thus, $R_{\rm min}$=9.08 fm for dAu and 9.21 fm for dPb collisions. We will discuss the sensitivity to $R_{\rm min}$ later.

Since the photon spectrum scales as $1/k$, deuteron breakup is dominated by interactions near threshold, 2.23 MeV in the deuteron rest frame. There have been a number of measurements of deuteron breakup by low-energy photons. Our breakup cross section, Fig. 1, is based on measurements at 2.754 MeV [3], 4.45 MeV [4], $5.97<k<11.39$ MeV [5], and $15<k<75$ MeV [6]. For $k<4$ MeV, we use the cross sections calculated with "Approximation III" in Table 1 of Ref. [7] since this approximation matches the 2.754 MeV data point. In the region $20<k<440$ MeV, we rely on a fit to the data [8]. For $440<k<625$ MeV, we use a slightly earlier fit [9]. We extrapolate this fit to 2 GeV with some loss in accuracy. At higher energies, QCD counting rules predict that σ_d should drop rapidly with energy [10]. Thus we neglect energies above 2 GeV.

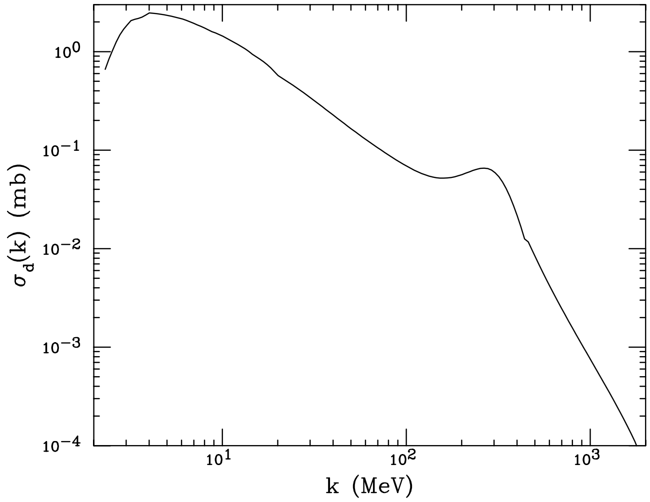

FIG. 1. Cross section for deuteron photodissociation as a function of photon energy, in the deuteron rest frame.

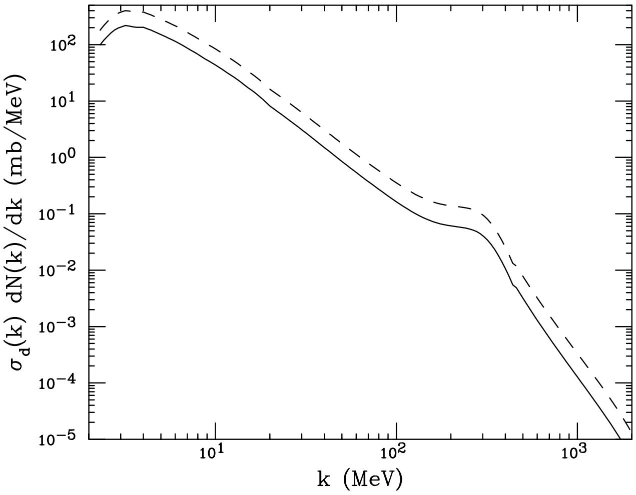

FIG. 2. Photon-flux weighted cross section for deuteron photodissociation, in the deuteron rest frame, for *d*Au at RHIC (solid line) and *d*Pb at the LHC (dotted line).

The integrand of Eq. (1) is shown in Fig. 2. The integrated photodissociation cross section is 1.24 b for deuterium-gold collisions at 200 GeV/nucleon center-of-mass energy, as currently studied at Relativistic Heavy Ion Collider (RHIC). At a luminosity of $4\times10^{28}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ [11], this is 50 000 interactions/s. For deuterium-lead collisions at 6.2 TeV/nucleon, as may be studied at the LHC, the calculated cross section is 2.35 b. At a luminosity of $2.7\times10^{29}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ [12], there will be 650 000 interactions/s. These cross sections are comparable to the calculated hadronic cross sections at the RHIC, 2.26 ± 0.10 b [13] and $2.37^{+0.13}_{-0.12}$ b [14], and slightly larger than the hadronic cross sections at the LHC. The quoted 4% uncertainty in Ref. [13] includes only the deuteron wave function.

The accuracy of the photodissociation cross section depends on the data from which it is derived. The most important photon energy range is below 10 MeV. Above 5.9 MeV, the data are quite accurate with uncertainties well below 5%. The 2.754-MeV data point also has only a 3.2% error. Unfortunately, at intermediate energies, the only data are from a 1952 measurement at 4.45 MeV with a 7% uncertainty. The theoretical extrapolation from lower energies should be more accurate than the data in this range. We estimate that the uncertainty in σ_d contributes a 4% error to the total dA cross sections.

Another uncertainty arises from the truncation of the photon spectrum. With the rapidly falling spectrum, stopping the calculation at 500 MeV reduces the photodissociation cross section by less than 0.1%. We estimate that the truncation introduces an error of less than 0.5% into the calculation.

The other important uncertainty in the cross section is in R_{min}. The charge radii of heavy ions are well measured [15], but the radii of the matter distribution may be 0.1–0.3 fm larger [16]. In addition, heavy ions can have non-negligible densities even at quite large distances. The deuteron wave function is complex, making an accurate geometric calculation quite difficult. However, because the photon energies are so low, the choice of R_{min} is not important. For gold at RHIC, increasing R_{min} by 2 fm only reduces the cross section by 1.8%, while for lead at the LHC, a 2 fm increase reduces it by 1.1%.

In addition to photodissociation, diffraction can induce deuteron dissociation. The heavy nucleus absorbs part of the deuteron wave function, leaving two independent nucleons in the outgoing state. For a completely black (absorptive) target nucleus with radius R_A, the diffractive dissociation cross section is [17,18]

$$\sigma_{\mathrm{diff}}=\frac{\pi}{3}[2\ln(2)-0.5]R_A R_d\,. \tag{3}$$

We find $\sigma_{\mathrm{diff}}=136$ mb for gold and $\sigma_{\mathrm{diff}}=139$ mb for lead. Since heavy nuclei are not completely black, this approach probably overestimates the cross sections slightly. However, since diffractive breakup is a small fraction of the total cross section, $\sigma=\sigma_{\mathrm{diss}}+\sigma_{\mathrm{diff}}$, we do not correct for the partial transparency.

We estimate the overall uncertainty in the dissociation cross section to be less than 5%, comparable to that of the hadronic deuterium-ion cross sections. The uncertainties in the hadronic radii of heavy ions and in the reaction geometry are at least as problematic as for hadronic interactions.

Experimentally, photodissociation has a clean signature: a proton and a neutron with roughly the beam momenta and no other visible reaction products. Other photonuclear interactions can break up the deuteron and create additional particles, but they represent a small fraction of the photodissociation cross section. The resulting neutron and proton can be detected in a zero degree calorimeter [19] and a forward proton calorimeter, respectively. Because of the small excitation energies, even small calorimeters will have good acceptance for the reaction products.

One final experimental issue is the background. Deuteron–beam-gas interactions might mimic photodissociation. However, in beam-gas interactions the proton or the neutron will usually lose a large fraction of its energy, allowing these events to be rejected. The beam-gas background can be measured by momentarily separating the beams to stop the collisions. With this check, deuteron breakup would be a useful calibration reaction for van der Meer scans of absolute luminosity [20], and, in routine operations, as a luminosity monitor. Because of the high rates, a neutron calorimeter alone will likely suffice for the dissociation studies. In many respects, the use of deuteron photodissociation parallels the use of mutual Coulomb dissociation in heavy-ion collisions [21].

Photodissociation can be used as an impact-parameter tag for studying other ultraperipheral collisions, as is done for mutual Coulomb dissociation [22]. The final state neutron (or proton) provides a tag of a moderate impact-parameter encounter. The probability of photodissociation at impact-parameter b, $P(b)$, is calculated using the impact-parameter-dependent photon flux [23]:

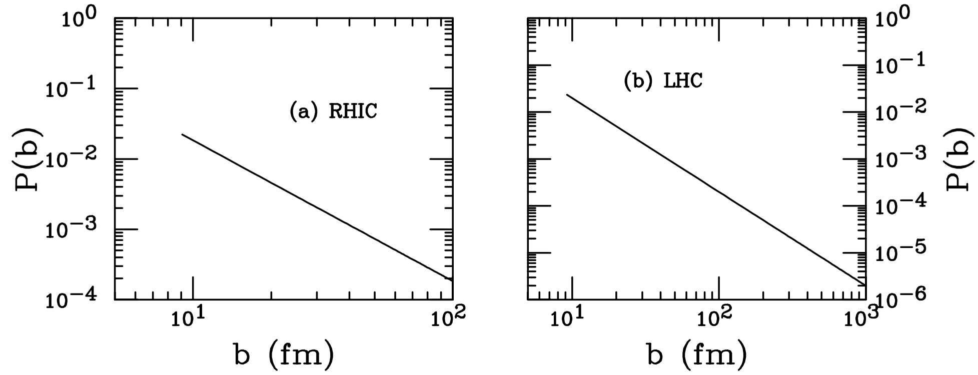

FIG. 3. Breakup probability $P(b)$ as a function of impact parameter b, for dAu at the RHIC (a) and dPb at the LHC (b).

$$P(b)=\int \frac{d^3N}{dkd^2b}\sigma_d(k)dk, \tag{4}$$

$$\frac{d^3N}{dkd^2b}=\frac{Z^2\alpha k}{\Gamma^2\pi^2}[K_1^2(x)+K_0^2(x)/\Gamma^2] \tag{5}$$

and here $x=kb/\hbar c\Gamma$. As long as $x<1$ for the important photon energies, $2<k<10$ MeV, $P(b)\approx 1/b^2$ and $d\sigma/db \approx 1/b$. This condition holds for $b<0.4$ nm at RHIC and $b<0.4$ μm at the LHC. Photodissociation can thus occur at extremely large impact parameters! The breakup probability as a function of b is given in Fig. 3. At an impact parameter of 10 fm, the probability of deuteron breakup is 1.8% for dAu collisions at the RHIC, dropping to 0.1% at 45 fm. These probabilities are somewhat lower than for mutual Coulomb breakup in AA collisions but should still be a useful tag.

Diffractive dissociation can occur when there is some overlap between the ion and the deuteron wave functions. Including this contribution would increase the total breakup probabilities slightly for $b<20$ fm.

In conclusion, we find that the cross section for deuteron breakup in dAu collisions at RHIC is 1.38 b, while at the LHC, the cross section for dissociation in dPb collisions is 2.49 b. Both cross sections have an estimated error of 5%. This reaction has a well-determined cross section and a clean signature, giving its utility as a ‘‘calibration’’ for luminosity measurement and monitoring and as a trigger for other ultraperipheral collisions.

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