Probing the quantum-mechanical equivalent-photon spectrum for electromagnetic dissociation of relativistic uranium projectiles

Th. Rubehn*
Nuclear Science Division, Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720

W. F. J. Müller and W. Trautmann
Gesellschaft für Schwerionenforschung (GSI), Planckstraβe 1, D-64291 Darmstadt, Germany

(Received 6 December 1996)

Electromagnetic fission cross sections for the reactions U + (Be, C, Al, Cu, In, Au, U) at $E/A = 0.6$ and 1.0 GeV are compared to theoretical calculations using recently proposed quantum-mechanical equivalent-photon spectra. In contrast to semiclassical calculations, systematically lower cross sections are obtained that cannot reproduce the experimental results. Since electromagnetic fission cross sections are virtually independent of the excitation of the double giant dipole resonance (DGDR), this conclusion is not influenced by the strength of the DGDR. [S0556-2813(97)00108-8]

PACS number(s): 25.75.−q, 25.85.Ge, 27.90.+b

The availability of relativistic heavy-ion beams has enabled systematic studies of electromagnetic excitation processes in nuclei [1]. Generally, the electromagnetic interaction between the projectile and the target nuclei is described by the exchange of virtual photons. Due to the almost quadratic dependence on the charge of the reaction partner and due to the fast time variation of the Lorentz-contracted electromagnetic field, electromagnetic cross sections are rather large for relativistic heavy-ion collisions; projectile energies of ~1 GeV/nucleon allow for an effective excitation of the giant resonances (10–30 MeV). When the nucleus is excited above its particle emission threshold or, in the case of fission, above its fission threshold, it may then dissociate according to the appropriate branching ratio. Experimentally, various decay branches have been investigated, such as γ rays, neutron emission, and fission, see, e.g., Refs. [1–20]. Almost exclusively, all the experimental data have been compared with calculations using the semiclassical Weizsäcker-Williams method of virtual photons [21–24] which has been shown to lead to an appropriate description of the process [24].

Recently, Benesh, Hayes, and Friar have presented new quantum-mechanical descriptions of the equivalent-photon spectra for electromagnetic heavy-ion collisions [25]. This work has extended previous studies [26,27] by examining the sensitivity on nuclear structure inputs. Electromagnetic excitation cross sections are calculated using the first Born approximation. Finally, a model is presented that gives simple quantum-mechanical expressions for the $E1$ and $E2$ equivalent-photon spectrum which can be used with measured photoabsorption cross sections in exactly the same way as the usual semiclassical expression.

Electromagnetic dissociation (EMD) cross sections for a specific decay channel Ψ can—generally—be expressed by

$$\sigma_{\rm EMD}^{\Psi}=\int[\sigma_{\gamma,\Psi}^{E1}n^{E1}(\omega)+\sigma_{\gamma,\Psi}^{E2}n^{E2}(\omega)]d\omega, \qquad (1)$$

where σ_γ is the photodissociation cross section and $n(\omega)$ is the intensity of photons with energy ω. The indices $E1$ and $E2$ indicate the multipolarities. While most semiclassical calculations make use of a cutoff parameter $b_{\rm min}$ in coordinate space to account for electromagnetic contributions only, the quantum-mechanical description introduces a cutoff parameter in momentum space [25]:

$$q_{\rm max}=1/b_{\rm min}=\{1.34[A_P^{1/3}+A_T^{1/3}-0.75(A_P^{-1/3}+A_T^{-1/3})]\}^{-1}, \qquad (2)$$

where A_P and A_T are the mass numbers of the projectile and target, respectively [28]. It has been shown that the used parametrization of $b_{\rm min}$ allows for a good description of the total nuclear reaction cross section [29].

In this paper, we will not discuss the quantum-mechanical ansatz *per se* which has been presented in Ref. [25]; this issue will be addressed elsewhere [30]. However, we shall apply the given quantum-mechanical virtual photon spectra to calculate electromagnetic dissociation cross sections of relativistic heavy-ion collisions. Comparisons between these calculations and semiclassical calculations on one hand and experimental results on the other hand will be discussed.

In a previous work, electromagnetic fission (EMF) of ^{238}U projectiles has been experimentally studied [17] using the ALADIN spectrometer at the heavy-ion synchrotron at GSI, Darmstadt. Seven different targets (Be, C, Al, Cu, In, Au, and U) have been bombarded at 0.6 and 1.0 GeV/nucleon. Experimental details on the measurements and the setup can be found in Refs. [17,31,32]. In Fig. 1, the deduced electromagnetic fission cross sections are shown as a function of the charge number of the target for both bombarding energies.

For comparison, both the semiclassical, based on the Weizsäcker-Williams method, and the quantum-mechanical calculations have been performed in the same fashion using Eq. (1): the same code has been used albeit with different equivalent photon spectra. The use of parametrizations of the photodissociation cross sections $\sigma_{\gamma,\rm total}$ [33], the fission

*Electronic address: TRubehn@lbl.gov

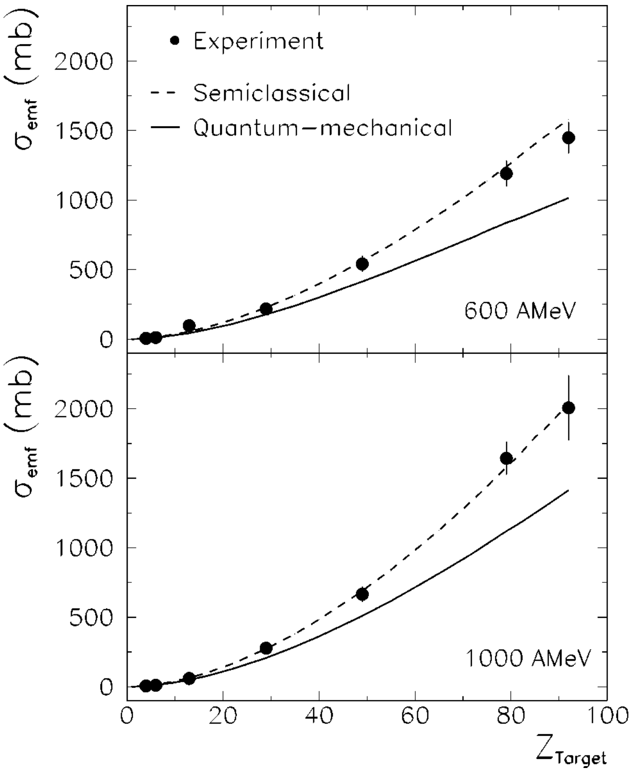

FIG. 1. Electromagnetic fission cross sections for the reactions ^{238}U + (Be, C, Al, Cu, In, Au, U) at E/A = 600 and 1000 MeV (from Ref. [17]). For comparison, theoretical results are shown using both the semiclassical (dotted line) [17] and the quantum mechanical descriptions (full line) [25] of the photon spectra.

probability and the cutoff parameter where nuclear interactions become dominant [28] has already been discussed previously [17].

While the semiclassical calculations can well reproduce the experimental data, the quantum-mechanical calculations give significantly lower cross sections. This is due to a reduced photon flux in the quantum-mechanical description. Note that this discrepancy is larger than the uncertainties connected with the choice of the cutoff parameter or the resonance parameters (see, e.g., Refs. [17,18]): the use of the Kox parametrization [34] results even in lower cross sections (~15%), whereas the use of photodissociation cross sections of Ref. [35], known to be systematically high [36–39], will lead to about 15% higher cross sections but still to an underprediction of the order of 15%. The experimental data can only be reproduced by the quantum-mechanical calculations if the cutoff parameter in momentum space q_{max} is artificially increased by 30%. For the reaction ^{238}U + ^{238}U, this results in a value of b_{min} = 12.5 fm compared to b_{min} = 16.3 fm from Eq. (2). This value seems too small to be associated with a total absorption radius and is not in agreement with recent investigations of the total reaction cross sections (see, e.g., Ref. [29]). While the equivalence between the sharp and smooth cutoff b_{min} has been shown to be valid in coordinate space [11], it seems to be invalid for a cutoff $q_{max}=1/b_{min}$ in momentum space [30].

The calculations predict nearly the same cross sections for electromagnetic fission, whether or not the possibility of two phonon excitation is included. This is due to the fact that the higher fission probability in the energy regime of the double giant dipole resonance (DGDR) is to a large extent compensated by the redistribution of cross section from one-photon to that of two-photon processes [17]. Therefore, the results of the calculations are almost independent of the strength of the DGDR as long as EMF cross sections are discussed. The comparison of calculated EMF cross sections with experimental data is thus *virtually independent* of the excitation of the DGDR. This holds, in particular, for the present comparison using the quantum-mechanical photon spectra presented in Ref. [25] which — in contrast to semiclassical photon spectra — fail to describe the experimental results.

While the electromagnetic fission cross sections alone are not sufficient to draw conclusions on the strength of the DGDR, other features of EMF data provide evidence for it: The asymmetry of the fission fragment charge distribution is known to be very sensitive to the excitation energy distribution. The asymmetry is usually expressed by the peak-to-valley ratio of the double humped charge distribution. In two independent experiments, a peak-to-valley ratio of 7.6 ± 2.6 and 7.1 ± 1.0, respectively, has been found [17,19]. Calculations show that the excitation of the single phonon states alone would result in a significantly higher peak-to-valley ratio of 16 ± 3, while calculations which account for the excitation of the DGDR can reproduce the experimental findings. Therefore, the low peak-to-valley ratio has been interpreted as a clear evidence of the DGDR excitation. This conclusion is also supported by the measurement of the proton odd-even effect of the fission fragment distribution [17]. We note that these quantities are completely independent of the integrated EMF cross sections.

For the electromagnetic one-neutron removal channel [5–8,10–12] it is also not possible to draw firm conclusions about the excitation and the strength of the DGDR from cross sections only: It has been shown previously that the $1n$ cross sections calculated using multiphonon excitations of the GDR differ by only ~10% from simple calculations based upon the excitation of the one-phonon state only [10]. Due to the known uncertainties in the calculations the interpretation of the data is not unambiguous. Therefore, Aumann *et al.* have studied electromagnetic dissociation by measuring $1n$–$5n$ neutron removal cross sections for various reactions [10,12]. The $2n$, $3n$, $4n$, and $5n$ removal cross sections reflect the contributions with increasingly higher excitation energies. It has been shown that these data cannot be understood without the excitation of the DGDR which accounts for the largest fraction of the cross section in the $2n, 3n, \ldots,$ channels [10,12]. These measurements and other evidence for the DGDR [2–4,20] contradict the concluding statement of Benesh, Hayes, and Friar [25] saying that the quantum-mechanical photon spectra leave little room for multiphoton mechanisms.[1]

In conclusion, we have applied the quantum-mechanical equivalent photon spectra presented in Ref. [25] in order to calculate EMF cross sections. The comparison with experi-

[1]We note that in Ref. [25] the expression ''multiphoton mechanisms'' is used when referring to multiphonon excitations. The two expressions are equivalent only in the linear harmonic case which is commonly used. For details, see Ref. [40].

mental electromagnetic fission data shows that, due to the significantly lower photon flux of the quantum-mechanical description, the experimental EMF cross sections are underpredicted by about 30%. Since uncertainties in the parametrizations are significantly smaller, we conclude that the quantum-mechanical photon spectrum presented in Ref. [25] is not able to describe the experimental results. This conclusion is independent of the strength of the DGDR since the higher fission probability compensates the effect of the redistribution of the cross sections.

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Physics Division of the U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.

[1] H. Emling, Prog. Part. Nucl. Phys. **33**, 729 (1994) and references therein.
[2] J. Ritman *et al.*, Phys. Rev. Lett. **70**, 533 (1993).
[3] R. Schmidt *et al.*, Phys. Rev. Lett. **70**, 1767 (1993).
[4] E. Wajda *et al.*, Nucl. Phys. **A569**, 141c (1994).
[5] M. T. Mercier, J. C. Hill, F. K. Wohn, C. M. McCullough, M. E. Nieland, J. A. Winger, C. B. Howard, S. Renwick, D. K. Matheis, and A. R. Smith, Phys. Rev. C **33**, 1655 (1986).
[6] J. C. Hill, F. K. Wohn, J. A. Winger, M. Khayat, K. Leininger, and A. R. Smith, Phys. Rev. C **38**, 1722 (1988).
[7] J. C. Hill, F. K. Wohn, J. A. Winger, M. Khayat, M. T. Mercier, and A. R. Smith, Phys. Rev. C **39**, 524 (1989).
[8] J. C. Hill and F. K. Wohn, Phys. Rev. C **39**, 2474 (1989).
[9] J. C. Hill, F. K. Wohn, D. D. Schwellenbach, and A. R. Smith, Phys. Lett. B **273**, 371 (1991).
[10] T. Aumann, J. V. Kratz, E. Stiel, K. Sümmerer, W. Brüchle, M. Schädel, G. Wirth, and J. C. Hill, Phys. Rev. C **47**, 1728 (1993).
[11] T. Aumann, C. A. Bertulani, and K. Sümmerer, Phys. Rev. C **51**, 416 (1995).
[12] T. Aumann *et al.*, Z. Phys. A **352**, 163 (1995).
[13] P. L. Jain, M. M. Aggarwal, M. S. El-Nagdy, and A. Z. M. Ismail, Phys. Rev. Lett. **52**, 1763 (1984).
[14] D. E. Greiner, H. Crawford, P. J. Lindstrom, J. M. Kidd, D. L. Olson, W. Schimmerling, and T. J. M. Symons, Phys. Rev. C **31**, 416 (1985).
[15] M. L. Justice, Y. Blumenfeld, N. Colonna, D. N. Delis, G. Guarino, K. Hanold, J. C. Meng, G. F. Peaslee, G. J. Wozniak, and L. G. Moretto, Phys. Rev. C **49**, R5 (1994).
[16] S. Polikanov *et al.*, Z. Phys. A **350**, 221 (1994).
[17] Th. Rubehn *et al.*, Z. Phys. A **353**, 197 (1995).
[18] Th. Rubehn *et al.*, Phys. Rev. C **53**, 3143 (1996).
[19] P. Armbruster *et al.*, Z. Phys. A **355**, 191 (1996).
[20] K. Boretzky *et al.*, Phys. Lett. B **384**, 30 (1996).
[21] E. Fermi, Z. Phys. **29**, 315 (1924).
[22] C. F. von Weizsäcker, Z. Phys. **88**, 612 (1934).
[23] E. J. Williams, Phys. Rev. **45**, 729 (1934).
[24] C. A. Bertulani and G. Baur, Phys. Rep. **163**, 299 (1988).
[25] C. J. Benesh, A. C. Hayes, and J. L. Friar, Phys. Rev. C **54**, 1404 (1996).
[26] C. J. Benesh and J. L. Friar, Phys. Rev. C **48**, 1285 (1993).
[27] C. J. Benesh and J. L. Friar, Phys. Rev. C **50**, 3167 (1994).
[28] C. J. Benesh, B. C. Cook, and J. P. Vary, Phys. Rev. C **40**, 1198 (1989).
[29] M. Hesse *et al.*, Z. Phys. A **355**, 69 (1996).
[30] G. Baur and C. A. Bertulani, Phys. Rev. C **56**, 581 (1997).
[31] Th. Rubehn *et al.*, Phys. Rev. C **53**, 993 (1996).
[32] A. Schüttauf *et al.*, Nucl. Phys. **A607**, 457 (1996).
[33] A. Veyssière, H. Beil, R. Bergère, P. Carlos, A. Lepetre, and K. Kernbath, Nucl. Phys. **A199**, 45 (1973).
[34] S. Kox *et al.*, Phys. Rev. C **35**, 1678 (1987).
[35] J. T. Caldwell, E. J. Dowdy, B. L. Berman, R. A. Alvarez, and P. Meyer, Phys. Rev. C **21**, 1215 (1980).
[36] W. Wilke, U. Kneissl, Th. Weber, H. Ströher, L. S. Cardman, P. T. Debevec, S. D. Hobbit, R. T. Jones, and A. M. Nathan, Phys. Rev. C **42**, 2148 (1990).
[37] H. Ries, G. Mank, J. Drexler, R. Heil, K. Huber, U. Kneissl, R. Ratzek, H. Ströher, T. Weber, and W. Wilke, Phys. Rev. C **29**, 2346 (1984).
[38] Th. Weber, R. D. Heil, U. Kneissl, W. Wilke, Th. Kihm, K. T. Knöpfle, and H. J. Emrich, Nucl. Phys. **A510**, 1 (1990).
[39] G. M. Gurewich, L. E. Lazareva, V. M. Mazur, G. V. Solodukhov, and B. A. Tulupov, Nucl. Phys. **A273**, 326 (1976).
[40] C. Volpe, F. Catara, Ph. Chomaz, M. V. Andres, and E. G. Lanza, Nucl. Phys. **A589**, 521 (1995).