BRIEF REPORTS

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Total and nuclear fission cross sections of ^{238}U at relativistic energies

Th. Rubehn,[1,2,*] R. Bassini,[3] M. Begemann-Blaich,[1] Th. Blaich,[4] A. Ferrero,[3] C. Groß,[1] G. Immé,[5] I. Iori,[3] G. J. Kunde,[1,†] W. D. Kunze,[1] V. Lindenstruth,[1,‡] U. Lynen,[1] T. Möhlenkamp,[6] L. G. Moretto,[2] W. F. J. Müller,[1] B. Ocker,[1] J. Pochodzalla,[1] G. Raciti,[5] S. Reito,[5] H. Sann,[1] A. Schüttauf,[7] W. Seidel,[6] V. Serfling,[1] W. Trautmann,[1] A. Trzcinski,[8] G. Verde,[5] A. Wörner,[1] E. Zude,[1] and B. Zwieglinski[8]

[1]*Gesellschaft für Schwerionenforschung, D-64220 Darmstadt, Germany*

[2]*Nuclear Science Division, Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720*

[3]*Dipartimento di Fisica, Università di Milano and INFN, I-20133 Milano, Italy*

[4]*Institut für Kernchemie, Universität Mainz, D-55099 Mainz, Germany*

[5]*Dipartimento di Fisica dell' Università and INFN, I-95129 Catania, Italy*

[6]*Forschungszentrum Rossendorf, D-01314 Dresden, Germany*

[7]*Institut für Kernphysik, Universität Frankfurt, D-60486 Frankfurt, Germany*

[8]*Soltan Institute for Nuclear Studies, 00-681 Warsaw, Hoza 69, Poland*

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Total fission cross sections of ^{238}U projectiles were measured at bombarding energies of 0.6 and 1 GeV per nucleon for seven different targets (Be, C, Al, Cu, In, Au, and U). It is found that all data points fall onto one curve, independent of bombarding energy, once the electromagnetic contribution to the total fission cross sections is subtracted. The abrasion-ablation model predicts a significantly weaker target dependence than observed, and underestimates the nuclear fission cross sections for the heavier targets.

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The investigation of fission of uranium at relativistic energies has become an interesting subject with the availability of heavy beams in the region of 1 GeV per nucleon at the heavy ion synchrotron SIS at GSI [1–6], which permits a continuation of earlier studies performed at the Bevalac [7,8]. Several experiments have, in particular, shown that fission of ^{238}U at relativistic energies is the result of both nuclear and electromagnetic interactions, whereby the latter is dominated by the excitation of the giant dipole resonance in uranium. Because of the large cross sections, electromagnetic fission is a suitable tool to study fission at low excitation energies, including experiments with secondary beams of radioactive fissile nuclei [9,10]. Furthermore, the investigation of electromagnetic fission fragment charge distributions has been shown to be sensitive to the excitation of the double giant dipole resonance in ^{238}U [3,4].

Recently, relativistic fission of uranium has been investigated to study viscosity effects [11]; these are directly correlated with possible transient time effects in the nuclear fission process which have been discussed for several years [12,13]. In Ref. [11], several experimental *total* fission cross sections over a broad range of relativistic bombarding energies are compared to the presently widely used abrasion-ablation model [11,14]. Uncertainties of the magntitude of the electromagnetic contribution to the total fission cross sections, due to the lack of precise measurements at that time, entered into this comparison. The ambiguity connected with the choice of the impact parameter cutoff, below which nuclear processes are dominant, had limited the accuracy of previous measurements and calculations of electromagnetic fission cross sections; see, e.g., Ref. [15].

More recently, we have reported on a study of electromagnetic fission of uranium after collisions with seven different targets; good agreement between the experimental data and extended Weizsäcker-Williams calculations, based on the parametrization proposed by Benesh, Cook, and Vary [16], has been found [3]. A similar conclusion was reached by Hesse *et al.* [5]. These results show that the electromagnetic fission process is well enough understood that the nuclear fission process can be determined by subtraction. We use this method and, in the present paper, we present the target dependence of the total and the nuclear fission cross sections of uranium projectiles. The latter are compared to results obtained in other experiments and to predictions of the abrasion-ablation model [11].

The ALADIN forward spectrometer [17] at the heavy-ion synchrotron SIS at GSI was used to investigate fission of projectilelike nuclei. Seven different targets (Be, C, Al, Cu, In, Au, and U) with thicknesses between 185 and 800

*Electronic address: TRubehn@lbl.gov

†Present address: National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824.

‡Present address: Nuclear Science Division, Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720.

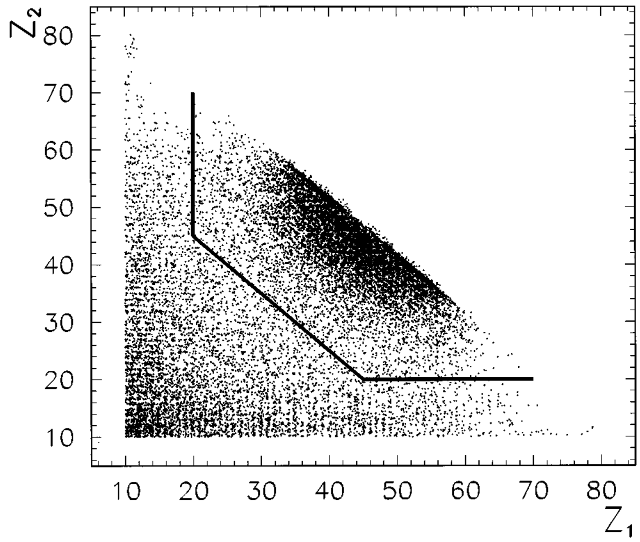

FIG. 1. Correlation of the two largest atomic numbers Z_1 and Z_2 as measured for the reaction U + U at 1 GeV per nucleon and a threshold $Z_i \geqslant 8$ for the two fragments. The solid line represents the adopted definition of fission.

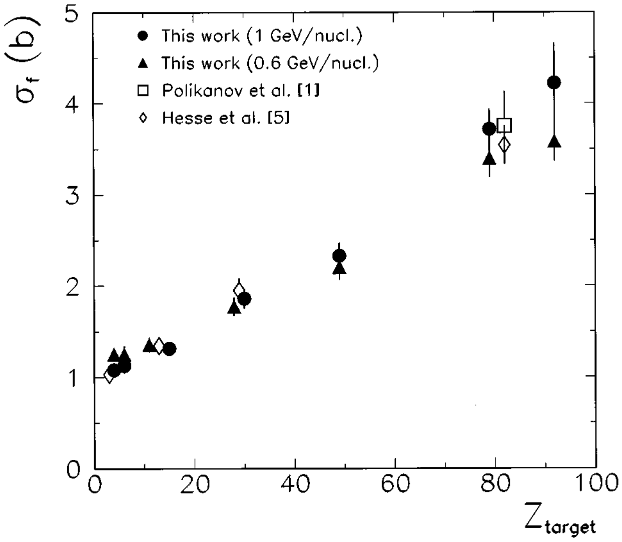

FIG. 2. Total fission cross sections of ^{238}U at energies between 0.6 and 1 GeV per nucleon. For comparison, experimental values of Refs. [1,5] have been included. In order to make the figure more legible, some data points have been slightly shifted horizontally.

mg/cm^2 were bombarded with ^{238}U projectiles at incident energies of 0.6 and 1 GeV/nucleon. The fission fragments of these relativistic projectiles were emitted into a cone of polar angles less than 3°, with respect to the beam axis. The geometrical acceptance of the ALADIN spectrometer ($\pm 9.2°$ in horizontal and $\pm 4.3°$ in vertical direction) was sufficient to detect both fission fragments simultaneously. Their atomic numbers Z and their trajectories were measured with the ionization chamber MUSIC positioned behind the dipole magnet ALADIN. A description of the experimental setup can be found in Refs. [3,6].

In Fig. 1, we show the correlation of the two largest atomic numbers as measured for the reaction U + U at a bombarding energy of 1 GeV per nucleon; Z_1 and Z_2 were randomly chosen to be the largest fragment in order to symmetrize the graphical representation. A relatively smooth transition from fission to multifragmentation is observed. We have selected the fission fragments according to the condition $[(Z_1 > 20) \wedge (Z_2 > 20) \wedge (Z_1 + Z_2 > 60)]$; this polygon follows the valley of the distribution. The exact choice of the polygon is not crucial for the present study because of the low intensity in the valley region [18]. The detection efficiency of 87% at 0.6 GeV and 81% at 1 GeV per nucleon, due to the finite double-hit resolution of the MUSIC detector, was taken into account [3].

In Fig. 2, we show the extracted total fission cross sections as a function of the atomic number of the target at 0.6 and 1 GeV per nucleon. The observed strong increase with Z_{target} is due to the electromagnetic contribution [3]. For comparison, we include data from measurements of Hesse *et al.* at 0.75 GeV/nucleon [5] and Polikanov *et al.* at 1 GeV/nucleon [1]. As already pointed out by the authors of Ref. [5], the measurement of Greiner *et al.* at 0.9 GeV/nucleon [8] seems systematically low in comparison to those of the other groups; therefore, we neglect these results in the further discussion.

In order to make a quantitative comparison of the fission cross sections measured at several bombarding energies, we subtract the contribution of electromagnetic fission:

$$\sigma_f^{\mathrm{nucl}} = \sigma_f - \sigma_f^{\mathrm{emd}}. \tag{1}$$

This ansatz is a good approximation since the interference term between the nuclear and the Coulomb transition amplitudes is shown to be very small: Benesh *et al.* have concluded that only (0.3–0.6)% of the electromagnetic cross section would correspond to this interference term [16]. The electromagnetic fission cross sections are obtained from extended Weizsäcker-Williams (WW) calculations which take into account the excitation of the single and the double giant dipole resonance and of the giant quadrupole resonance in ^{238}U [3,19]. Generally, these calculations approximate the electromagnetic field by an equivalent virtual photon flux. The absorption of a virtual photon will excite the nucleus which can then deexcite according to the branching ratios of the various channels. In our recent study of the electromagnetic fission process, the good agreement between the experimental and the theoretical results has been demonstrated [3]. Besides the cross sections, this also holds for quantities like the asymmetry of the fission fragment charge distributions and the charge odd-even effect, which are very sensitive to the deposited excitation energy. It should therefore be justified to make use of the calculated values for electromagnetic fission in order to determine the nuclear fission cross sections, also for the data from the other experiments.

In Table I, we give the values of the measured total fission cross sections, the theoretical results for electromagnetic fission, and finally the nuclear fission cross sections of our measurement and those obtained in other experiments [1,5]. The nuclear fission cross sections are compared in Fig. 3. Within the uncertainties, almost all values fall onto one curve, in agreement with the expectation that the energy dependence should be small in the interval between 0.6 and 1 GeV/nucleon [1]. The dashed line shows the results of a

TABLE I. Total and nuclear fission cross sections for several reactions. The electromagnetic contribution has been calculated according to the Weizsäcker-Williams method. The superscripts 1 and 2 in the first column indicate data from Refs. [5] and [1], respectively. The last column gives the nuclear fission cross sections as predicted by the abrasion-ablation code [11,14].

Target	E/A (GeV)	σ_f (barns)	σ_f^{emd} (barns)	σ_f^{nucl} (barns)	$\sigma_{f,th}^{\mathrm{nucl}}$ (barns)
Be	0.6	1.25 ± 0.07	0.006	1.24 ± 0.07	1.13
Be	1.0	1.08 ± 0.07	0.007	1.07 ± 0.07	1.13
Be[1]	0.75	1.03 ± 0.10	0.007	1.02 ± 0.10	1.13
C	0.6	1.25 ± 0.09	0.014	1.24 ± 0.09	1.18
C	1.0	1.13 ± 0.08	0.015	1.11 ± 0.08	1.18
Al	0.6	1.35 ± 0.08	0.055	1.32 ± 0.08	1.22
Al	1.0	1.31 ± 0.08	0.064	1.25 ± 0.08	1.22
Al[1]	0.75	1.34 ± 0.09	0.059	1.28 ± 0.09	1.22
Cu	0.6	1.77 ± 0.10	0.228	1.54 ± 0.10	1.35
Cu	1.0	1.86 ± 0.11	0.273	1.59 ± 0.11	1.35
Cu[1]	0.75	1.95 ± 0.13	0.246	1.70 ± 0.13	1.35
In	0.6	2.21 ± 0.14	0.560	1.65 ± 0.14	1.46
In	1.0	2.33 ± 0.14	0.690	1.64 ± 0.14	1.46
Au	0.6	3.40 ± 0.21	1.240	2.16 ± 0.21	1.52
Au	1.0	3.72 ± 0.22	1.577	2.14 ± 0.22	1.52
Pb[1]	0.75	3.54 ± 0.21	1.458	2.08 ± 0.21	1.55
Pb[2]	1.0	3.75 ± 0.38	1.676	2.07 ± 0.38	1.55
U	0.6	3.58 ± 0.21	1.581	2.00 ± 0.21	1.58
U	1.0	4.22 ± 0.44	2.036	2.19 ± 0.44	1.58

calculation assuming a proportionality of the nuclear fission cross section to the total nuclear reaction cross section, $\sigma_f^{\mathrm{nucl}} = k \cdot \sigma_{\mathrm{reac}}$. Here, the target dependence of σ_{reac} has been taken from a parametrization by Benesh, Cook, and Vary [16]; the fitted proportionality constant results in $k = 0.27 \pm 0.04$ and allows a surprisingly good description of the data.

We have, furthermore, performed theoretical calculations with the widely used abrasion-ablation model [2,11,14] in the version described in Ref. [11]. This model makes use of the participant-spectator picture [20]: During the abrasion phase the system divides into the overlap and the nonoverlap zones. The nucleons of the overlap zone form a hot fireball while the nucleons of the nonoverlap zone continue to move almost undisturbed with the initial velocities of the projectile and target, respectively. In this geometrical picture, the number of nucleons removed from a nucleus only depends on the impact parameter which determines the overlap volume. Thus, the mass numbers of the product nuclei and their cross sections are correlated functions of the impact parameter. The average excitation energy of a prefragment is given by 27 MeV per abraded nucleon which was determined empirically [22,14]. The following second stage, the so-called ablation or evaporation process, is described by means of statistical model calculations. The fission channel is, in particular, included in the deexcitation cascade [11]. For a consistent description of the nuclear fissilities at high excitation energies, a correct choice of the asymptotic values of the level-density parameters is very important. As proposed by Ignatyuk *et al.*, we have used the following set of input parameters: $\alpha_V = 0.073$, $\alpha_S = 0.095$, and $\alpha_K = 0.0$ [11]. These coefficients correspond to the volume, surface, and curvature components of the single-particle level densities; they are based on the single-particle schemes of the Woods-Saxon potential [21]. As pointed out in Ref. [11], a different choice of these parameters will change the fission cross sections significantly. The relative target dependence, however, is not affected.

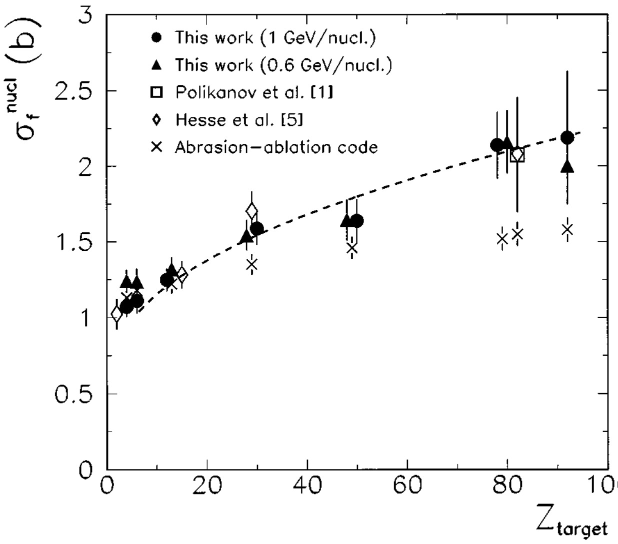

FIG. 3. Nuclear fission cross sections of ^{238}U at energies between 0.6 and 1 GeV per nucleon; the values have been obtained by subtraction of the electromagnetic contribution. In order to make the figure more legible, some of the data points have been slightly shifted horizontally. The dashed line shows the target dependence as predicted for the reaction cross section in Ref. [16]. For comparison we show the results of the abrasion-ablation model calculations using the parameters as proposed in Ref. [11].

In Table I and Fig. 3, we show the results of the abrasion-ablation model calculations. The energy independence of the nuclear fission cross section that has been observed experimentally is reproduced [1]. However, the theoretical values show a significantly weaker target dependence, leading to smaller cross sections for the heavier targets. This finding is in agreement with results of our previous studies of electromagnetic fission of uranium: The nuclear contribution to selected fission channels exhibited a stronger target dependence than predicted by geometrical models [3]. Since the process of additional excitation of the prefragment by nucleons emitted from the fireball is rather complex, it might well be that the excitation energy of 27 MeV per abraded nucleon, empirically determined for Au + Al reactions [22], is target dependent. This would change the target dependence of the cross sections predicted by the abrasion-ablation model.

Even though the main conclusion of Ref. [11] will not be affected, we note that the comparison between the reported experimental and theoretical fission cross sections would be less favorable if the nuclear and electromagnetic contributions were considered separately. The electromagnetic fission cross sections, which in the model were based on a global Z^2/A systematic, are significantly higher than those reported, e.g., in Refs. [3,4]. The observed agreement based on the comparison of total fission cross sections might therefore be caused by a relatively high electromagnetic contribution.

In conclusion, we have measured total fission cross sections of ^{238}U at bombarding energies of 0.6 and 1 GeV per nucleon using seven different targets between beryllium and uranium. The nuclear fission cross sections have been determined by subtraction of the calculated electromagnetic fission cross sections. Once this has been done, all available data fall quite precisely onto one curve. We have, furthermore, performed abrasion-ablation model calculations of the nuclear fission cross sections. The target dependence of the theoretical values, however, is significantly weaker than the one observed experimentally, and the nuclear fission cross sections for the heavier targets are underestimated. Our results increase the number of available fission cross sections at relativistic energies significantly, and will therefore allow more quantitative comparisons to theoretical models for the nuclear fission process.

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[1] S. Polikanov, W. Brüchle, H. Folger, E. Jäger, T. Krogulski, M. Schädel, E. Schimpf, G. Wirth, T. Aumann, J.V. Kratz, N. Stiel, and N. Trautmann, Z. Phys. A **350**, 221 (1994).

[2] H.-G. Clerc *et al.*, Nucl. Phys. **A590**, 785 (1995).

[3] Th. Rubehn *et al.*, Z. Phys. A **353**, 197 (1995).

[4] P. Armbruster, M. Bernas, T. Aumann, S. Czajkowski, H. Geissel, Ph. Dessagne, C. Donzaud, E. Hanelt, A. Heinz, M. Hesse, C. Kozhuharov, Ch. Miehe, G. Münzenberg, M. Pfützner, K.-H. Schmidt, W. Schwab, C. Stephan, K. Sümmerer, L. Tassan-Got, and B. Voss, Z. Phys. A (submitted).

[5] M. Hesse, M. Bernas, P. Armbruster, T. Aumann, S. Czajkowski, Ph. Dessagne, C. Donzaud, H. Geissel, E. Hanelt, A. Heinz, C. Kozhuharov, Ch. Miehe, G. Münzenberg, M. Pfützner, C. Röhl, K.-H. Schmidt, W. Schwab, C. Stephan, K. Sümmerer, and L. Tassan-Got, Z. Phys. A (submitted).

[6] Th. Rubehn *et al.*, Phys. Rev. C **53**, 993 (1996).

[7] P.L. Jain, M.M. Aggarwal, M.S. El-Nagdy, and A.Z.M. Ismail, Phys. Rev. Lett. **52**, 1763 (1984).

[8] 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).

[9] K.H. Schmidt *et al.*, Phys. Lett. B **325**, 313 (1994).

[10] M. Bernas *et al.*, Phys. Lett. B **331**, 19 (1994).

[11] A.V. Ignatyuk, G.A. Kudyaev, A. Junghans, M. de Jong, H.-G. Clerc, and K.-H. Schmidt, Nucl. Phys. **A593**, 519 (1995), and references therein.

[12] P. Grangé and H.A. Weidenmüller, Phys. Lett. **96B**, 26 (1980); P. Grangé, L. Jun-Qing, and H.A. Weidenmüller, Phys. Rev. C **27**, 2063 (1983); H.A. Weidenmüller and Z. Jing-Shang, *ibid.* **29**, 879 (1984); P. Grangé, S. Hassani, H.A. Weidenmüller, A. Gavron, J.R. Nix, and A.J. Sierk, *ibid.* **34**, 209 (1986).

[13] L.G. Moretto, K.X. Jing, R. Gatti, G.J. Wozniak, and R.P. Schmitt, Phys. Rev. Lett. **75**, 4186 (1995); Th. Rubehn, K.X. Jing, L.G. Moretto, L. Phair, K. Tso, and G.J. Wozniak in *Proceedings of the 12th Winter Workshop on Nuclear Dynamics*, Snowbird, Utah, 1996, edited by W. Bauer and G. D. Westfall (Plenum, New York, in press).

[14] T. Brohm and K.H. Schmidt, Nucl. Phys. **A569**, 821 (1994).

[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] C.J. Benesh, B.C. Cook, and J.P. Vary, Phys. Rev. C **40**, 1198 (1989).

[17] J. Hubele *et al.*, Z. Phys. A **340**, 263 (1991).

[18] V. Lindenstruth, Ph.D. thesis, Universität Frankfurt a.M., 1993; Th. Rubehn, Ph.D. thesis, Universität Frankfurt a.M., 1995.

[19] T. Aumann *et al.*, Z. Phys. A **352**, 163 (1995).

[20] G.D. Westfall, J. Gosset, P.J. Johansen, A.M. Poskanzer, W.G. Meyer, H.H. Gutbrod, A. Sandoval, and R. Stock, Phys. Rev. Lett. **37**, 1202 (1976).

[21] A.V. Ignatyuk, M.G. Itkis, V.N. Okolovich, G.N. Smirenkin, and A.S. Tishin, Yad. Fiz. **21**, 1185 (1975) [Sov. J. Nucl. Phys. **21**, 612 (1975)].

[22] K.-H. Schmidt, T. Brohm, H.-G. Clerc, M. Dornik, M. Fauerbach, H. Geissel, A. Grewe, E. Hanelt, A. Junghans, A. Magel, W. Morawek, G. Münzenberg, F. Nickel, M. Pfützner, C. Scheidenberger, K. Sümmerer, D. Vieira, B. Voss, and C. Ziegler, Phys. Lett. B **300**, 313 (1993).