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Charge pickup of ^{238}U at relativistic energies

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Cross sections for the charge pickup of ^{238}U projectiles were measured at $E/A = 600$ and 1000 MeV for seven different targets (Be, C, Al, Cu, In, Au, and U). Events with two fission fragments with a sum charge of 93 in the exit channel were selected. Due to the significant excitation energy, the majority of the produced Np nuclei fission instead of decaying by evaporation to residues. The observed cross sections can be well reproduced by intranuclear-cascade-plus-evaporation calculations and, therefore, confirm recent results that no exotic processes are needed to explain charge-pickup processes.

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The process of charge pickup by relativistic projectiles has been observed in numerous experiments. Projectiles between carbon and uranium have been studied in the energy regime of $E/A = 0.5$–2 GeV. With light projectiles, such as C, O, or Ne, cross sections below 1 mb were observed, but for heavier projectile nuclei cross sections on the order of tens of mb have been measured. Systematic studies reported a quadratic dependence of the cross sections on the mass of the projectile [1]. A recent compilation has been given by Nilsen *et al.* [2]. With the availability of gold beams from the Brookhaven National Laboratory Alternating Gradient Synchrotron (AGS) results on charge-exchange processes at $E/A \approx 11$ GeV were reported by various groups [2–5]. A weak dependence on the mass of the target nuclei (hydrogen to lead) was found. Furthermore, the extracted excitation functions show a significant decrease of the cross sections as the energy increases.

Recently Sümmerer *et al.* measured a complete experimental isotope distribution of Cs products formed in the charge-exchange reaction ^{129}Xe incident on an Al target at 790 MeV/nucleon [6]. The large cross sections for neutron deficient isotopes indicated a dominant contribution from evaporation during the formation of the final Cs fragments. Furthermore, it was shown that intranuclear-cascade-plus-evaporation calculations reproduced the observed yields for charge pickup and the known strong increase of the cross section as a function of the mass of the projectile [1]. According to the calculations, the cross section of the prefragment production increases approximately linearly with the mass of the projectile but the evaporation of protons depletes these yields and leads to the observed lower cross sections, especially for small neutron-deficient nuclei [6]. Experimental studies of the charge-pickup process for the heaviest projectiles available allow for further tests of the prediction that the cross sections should deviate significantly from the A^2 dependence observed for light and intermediate projectiles. Therefore, an extension of the existing systematics beyond $A_{\text{proj}} = 200$ was the main motivation of the present work to study charge pickup of ^{238}U projectiles.

Charge pickup of uranium at $E/A = 960$ MeV was investigated by Westphal *et al.* [7] who used a track-etch detector with high sensitivity. Not a single neptunium track ($Z = 93$) was found which led to an upper limit of 8 mb for the production cross section. It was concluded that this was due to the high fissibility of neptunium upon the deposition of a moderate excitation energy; 40 MeV was considered to be sufficient to ensure that more than 90% of the hot Np nuclei fission. This estimate is consistent with the observation of an apparent mean mass loss of five to seven nucleons associated with the charge pickup for heavy projectiles like gold and holmium [8,9].

In the present experiment the ALADIN forward spectrometer [10] at the heavy-ion synchrotron SIS at GSI was used to investigate charge pickup of uranium via fission of projectilelike nuclei. Seven different targets (Be,C,Al,Cu,In,Au,U) with thicknesses between 185 and 800 mg/cm^2 were bombarded with ^{238}U projectiles at incident energies of $E/A = 600$ and 1000 MeV. 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 (±9.2° in

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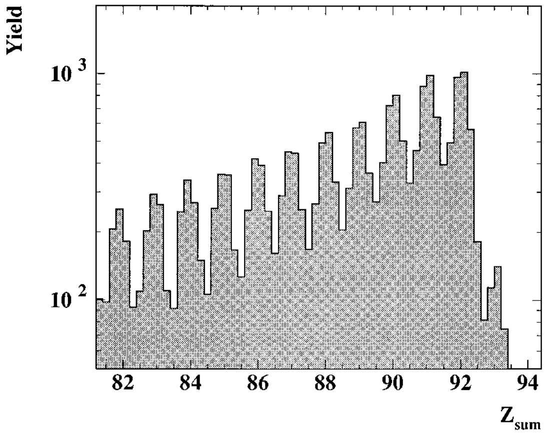

FIG. 1. Spectrum of the sum charge $Z_{\rm sum}$ of fission fragments from the reactions ^{238}U on Al at $E/A=1000$ MeV.

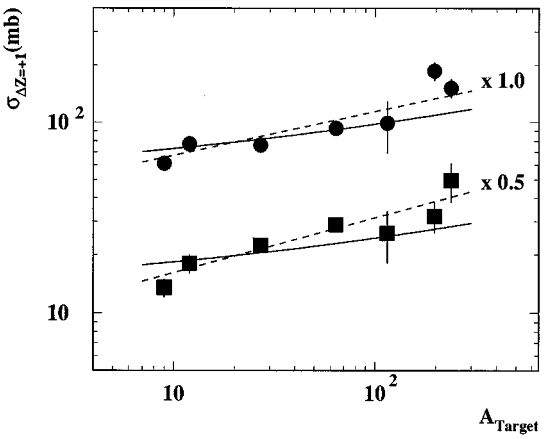

FIG. 2. Cross sections for charge pickup and subsequent fission of ^{238}U projectiles at $E/A=600$ (dots) and 1000 MeV (squares). The lines show power law fits (dashed lines) and fits to $A_t^{1/3}+A_p^{1/3}-0.75(A_t^{-1/3}+A_p^{-1/3})$ (solid lines). The error bars denote the statistical and systematic errors combined in quadrature.

horizontal and ±4.3° in vertical direction) was sufficient to detect both fission fragments simultaneously. The atomic numbers, positions, and angles of projectile fragments were measured with the ionization chamber MUSIC positioned behind the dipole magnet ALADIN. A description of the experimental setup can be found in Ref. [11]. With this setup a resolution of 0.6 [full width at half maximum (FWHM)] was achieved for the sum charge of fission fragments (see Fig. 1).

For the study of charge-pickup processes of uranium, fission events $[(Z_1>20) \wedge (Z_2>20) \wedge (Z_1+Z_2>60)]$ with a sum charge of 93 were selected. The experimental cross sections had to be corrected for nuclear interactions of the fission fragments in the target and in the materials of the detectors. To determine this effect, experimental total charge changing cross sections for various systems were used [12–14] and interpolations for typical fission fragments were made. Differences from the calculated total reaction cross sections were used as an estimate of the associated uncertainty. Due to the finite double-hit resolution in the MUSIC the detection efficiency was limited to 87% at $E/A=600$ MeV and 81% at $E/A=1000$ MeV. The cross sections were corrected for this effect. The angular distribution of the fission fragments was assumed to be isotropic in the c.m. system for the correction. This assumption is, however, not crucial [11].

In Fig. 2 and Table I we show the experimental cross sections for charge pickup of ^{238}U and subsequent fission as a function of the mass of the target. The dashed lines indicate power law fits to the data as suggested by Nilsen *et al.* [2] whereas the solid lines show the results of a linear fit to $A_t^{1/3}+A_p^{1/3}-0.75(A_t^{-1/3}+A_p^{-1/3})$ as may be expected for peripheral nuclear collisions [15]. Due to the experimental uncertainties, especially for heavy targets, no decision can be made which of the parametrizations gives a better description of the data. In a later discussion we will show that nearly the full cross section for charge pickup of ^{238}U can be found in the fission channel.

We should note that the dominant contribution to the systematic errors is due to the finite experimental charge resolution and the resulting partial overlap of the $Z_{\rm sum}=92$ and charge-93 channels. As we have shown in a previous paper [11], the cross section for electromagnetic fission leading to $Z_{\rm sum}=92$ increases approximately quadratically with the charge of the target. Therefore the ratio of the yield with $Z_{\rm sum}=93$–92 decreases strongly as the charge number of the target increases.

Following the suggestion of Sümmerer *et al.*, [6] intranuclear-cascade-plus-evaporation calculations were performed using the code ISAPACE [16–18]. At relativistic energies and very peripheral collisions, intranuclear-cascade (INC) calculations based on experimental free hadron-hadron cross sections were successful in describing experimental data; see e.g., Refs. [6,19]. The INC code ISABEL is, except for the quantum mechanical ingredient of the Pauli blocking, a purely classical model and accounts for the diffuseness of the nuclear surface. Nuclear charge exchange processes proceed in the model either via (n,p)-charge exchange collisions where a virtual charged pion is exchanged or by excitation of a Δ resonance with subsequent emission of a negative pion. The excited prefragments decay subsequently by light particle emission or by fission. This deexcitation is modeled by the statistical evaporation code PACE. To verify the validity of this description for fission reactions in the energy regime of $E/A=1$ GeV, we compared the calculated formation cross sections of uranium isotopes from the reac-

TABLE I. Experimental cross sections for charge pickup and subsequent fission of ^{238}U. Both the statistical (first values) and the systematical errors (second values) are given.

	$E/A=600$ MeV	$E/A=1000$ MeV
Target	$\sigma_{\Delta Z=+1}$ (mb)	$\sigma_{\Delta Z=+1}$ (mb)
Be	61 ± 3 ± 4	27 ± 2 ± 2
C	77 ± 2 ± 5	36 ± 2 ± 3
Al	76 ± 4 ± 4	45 ± 2 ± 3
Cu	93 ± 3 ± 5	58 ± 3 ± 4
In	99 ± 3 ± 30	52 ± 3 ± 16
Au	186 ± 9 ± 19	64 ± 3 ± 12
U	151 ± 4 ± 17	99 ± 6 ± 22

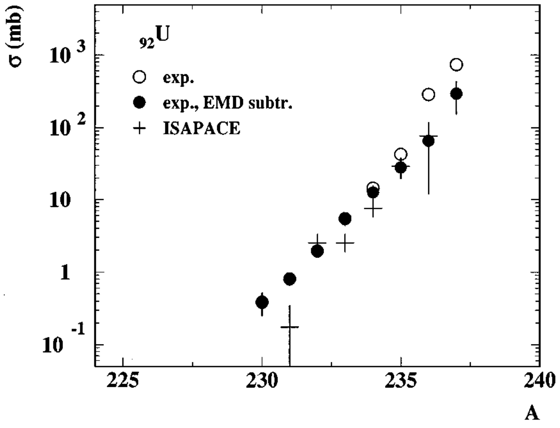

FIG. 3. Experimental cross sections for the production of uranium isotopes in the reaction ^{238}U + $^{\mathrm{nat}}$Cu at E/A = 950 MeV (open circles, data from Ref. [20]). The nuclear part of the cross sections (solid circles, obtained by subtracting the electromagnetic contribution) is compared to the results of ISAPACE calculations (crosses).

tion ^{238}U + $^{\mathrm{nat}}$Cu at a bombarding energy of 950 MeV/nucleon with experimental results [20]. The data include contributions from electromagnetic neutron removal processes [21]. In Fig. 3 we show both the experimental data and the results of ISAPACE calculations. A good description is achieved after calculated electromagnetic contributions [11] are taken into account. The precision of the calculation has been shown in a recent paper by Aumann *et al.* [21]; very good agreement between experimental and calculated cross sections for electromagnetic neutron removal of uranium has been reported.

A reasonable agreement is obtained for the charge-exchange process leading to the formation of Np and subsequent fission in the reaction ^{238}U + Al at 600 and 1000 MeV/nucleon; ISAPACE calculations result in cross sections of 74±6 mb and 59±5 mb, respectively. In Fig. 4, we present a comparison of charge-pickup cross sections in the energy regime of $E/A \approx 1$ GeV for different projectiles interacting with Al targets [2,6,8,22,23]. The experimental trend as a function of the mass of the projectile is correctly reproduced by ISAPACE calculations. We also show the results from ISABEL calculations, prior to evaporation. The production cross sections of prefragments with $\Delta Z = +1$ increases approximately linearly with the mass of the projectile. While the evaporation of neutrons does not change the cross sections, the evaporation of protons depletes the yields and lead to the formely discussed lower cross sections, especially for light nuclei where the Coulomb barriers hinder the evaporation of protons less than in the case of heavy nuclei. Therefore, the survival probability with respect to light charged particle emission increases from ~5% for iron to 80% in the case of uranium. Our results confirm the expected behavior [6] for the heaviest projectiles available.

An estimate of the excitation energy can be achieved from the number of evaporated neutrons. Our measurements of the fragments mass yield a broad distribution with a mean mass loss ΔA_{sum} of approximately 9 neutrons in total. After subtracting ~ 3 postscission neutrons [24] it can be estimated that about 6 neutrons were evaporated during the deexcitation of the formed Np nucleus. A comparable number of neutrons was found in other experiments using heavy projectiles like lanthanum, holmium, and gold [8,9]. Under the assumption that one neutron carries away 8 MeV, the total mass loss corresponds to a mean excitation energy of the prefragment going into the $\Delta Z = +1$ exit channel of roughly 50 MeV. This result is in good agreement with the experimental findings of Westphal *et al.* [9] and with ISAPACE calculations which predict a mean mass loss of ~9 neutrons from the Np prefragment ($\bar{A}_{\mathrm{pref}}$ = 237) and a fission probability of ~98% for events with $Z_{\mathrm{sum}} = 93$. Therefore, nearly the full pickup cross section is found in the fission channel.

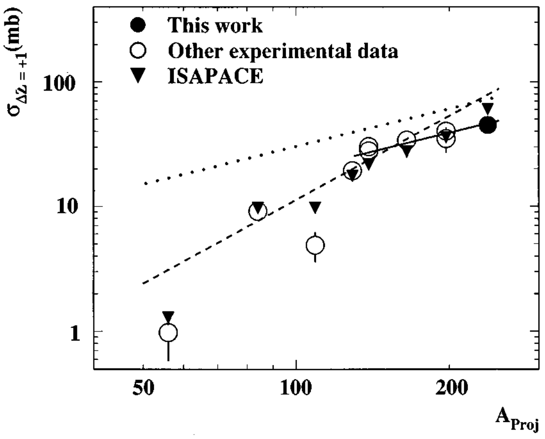

FIG. 4. Experimental cross sections for charge pickup as a function of the projectile mass from several measurements [2,6,8,22,23]. All data have been obtained by using an Al target. Both quadratic (dashed line) and linear (solid line) dependences are shown. For comparison the results of ISAPACE calculations are shown (triangles). The dotted line shows the results from ISABEL calculations, prior to evaporation.

In conclusion, we have measured the charge-pickup cross sections for relativistic ^{238}U projectiles by investigating the fission channel. Good agreement with intranuclear-cascade-plus-evaporation calculations is observed. As pointed out earlier by Sümmerer *et al.* [6], it is not necessary to invoke coherent processes to explain the observed cross sections for charge-pickup processes. Both experimental results and ISAPACE calculations show a mean mass loss for the fission fragments of approximately 9 neutrons in total caused by the deexcitation of the formed Np nucleus and the additional evaporation of ~3 fission neutrons. By looking at events with change changing processes, it can be estimated from the calculations that ~78% of the prefragments fission and another 20% decay via light charged particle emission. Thus, ~2% of the produced Np fragments are predicted to survive. This result is, however, consistent with the nonobservation of Np nuclei, reported in a previous publication [7].

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[1] Ren Guoxiao, P.B. Price, and W.T. Williams, Phys. Rev. C **39**, 1351 (1989).

[2] B.S. Nilsen, C.J. Waddington, W.R. Binns, J.R. Cummings, T.L. Garrard, L.Y. Geer, and J. Klarmann, Phys. Rev. C **50**, 1065 (1994).

[3] Y.D. He and P.B. Price, Phys. Lett. B **298**, 50 (1993); Y.D. He, Ph.D. thesis, University of California at Berkeley, 1993.

[4] S.E. Hirzebruch, E. Becker, G. Hüntrup, T. Streibel, E. Winkel, and W. Heinrich, Phys. Rev. C **51**, 2085 (1995).

[5] L.Y. Geer, J. Klarmann, B.S. Nilsen, C.J. Waddington, W.R. Binns, J.R. Cummings, and T.L. Garrard, Phys. Rev. C **52**, 334 (1995).

[6] K. Sümmerer, J. Reinhold, M. Fauerbach, J. Friese, H. Geissel, H.-J. Körner, G. Münzenberg, R. Schneider, and K. Zeitelhack, Phys. Rev. C **52**, 1106 (1995).

[7] A.J. Westphal, P.B. Price, and D.P. Snowden-Ifft, Phys. Rev. C **45**, 2423 (1992).

[8] J.R. Cummings, W.R. Binns, T.L. Garrard, M.H. Israel, J. Klarmann, E.C. Stone, and C.J. Waddington, Phys. Rev. C **42**, 2508 (1990).

[9] A.J. Westphal, Jing Guiru, and P.B. Price, Phys. Rev. C **44**, 1687 (1991).

[10] J. Hubele, P. Kreutz, J.C. Adloff, M. Begemann-Blaich, P. Bouissou, G. Imme, I. Iori, G.J. Kunde, S. Leray, V. Lindenstruth, Z. Liu, U. Lynen, R.J. Meijer, U. Milkau, A. Moroni, W.F.J. Müller, C. Ngô, C.A. Ogilvie, J. Pochodzalla, G. Raciti, G. Rudolf, H. Sann, A. Schüttauf, W. Seidel, L. Stuttge, W. Trautmann, and A. Tucholski, Z. Phys. A **340**, 263 (1991).

[11] Th. Rubehn, W.F.J. Müller, R. Bassini, M. Begemann-Blaich, Th. Blaich, A. Ferrero, C. Groß, G. Imme, I. Iori, G.J. Kunde, W.D. Kunze, V. Lindenstruth, U. Lynen, T. Möhlenkamp, L.G. Moretto, B. Ocker, J. Pochodzalla, G. Raciti, H. Sann, A. Schüttauf, W. Seidel, V. Serfling, W. Trautmann, A. Trzcinski, G. Verde, A. Wörner, E. Zude, and B. Zwieglinski, Z. Phys. A **353**, 197 (1995).

[12] W.R. Binns, T.L. Garrard, M.H. Israel, M.P. Kertzmann, J. Klarmann, E.C. Stone, and C.J. Waddington, Phys. Rev. C **36**, 1870 (1987).

[13] W.R. Webber, J.C. Kish, and D.A. Schrier, Phys. Rev. C **41**, 520 (1990).

[14] Y.D. He and P.B. Price, Z. Phys. A **348**, 105 (1994).

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

[16] Y. Yariv and Z. Fraenkel, Phys. Rev. C **20**, 2227 (1979).

[17] T. Blaich, M. Begemann-Blaich, M.M. Fowler, J.B. Wilhelmy, H.C. Britt, D.J. Fields, L.F. Hansen, M.N. Namboodiri, and T.C. Sangster, Phys. Rev. C **45**, 689 (1992).

[18] K.-H. Schmidt, K. Sümmerer, H. Geissel, G. Münzenberg, F. Nickel, M. Pfützner, M. Weber, B. Voss, T. Brohm, H.-G. Clerc, M. Fauerbach, J.-J. Gaimard, A. Grewe, E. Hanelt, M. Steiner, J. Weckenmann, C. Ziegler, and A. Magel, Nucl. Phys. **A542**, 699 (1992).

[19] K. Sümmerer, W. Brüchle, D.J. Morrissey, M. Schädel, B. Szweryn, and Yang Weifan, Phys. Rev. C **42**, 2546 (1990).

[20] H.-G. Clerc, M. de Jong, T. Brohm, M. Dornik, A. Grewe, E. Hanelt, A. Heinz, A. Junghans, C. Röhl, S. Steinhäuser, B. Voss, C. Ziegler, K.-H. Schmidt, S. Czajkowski, H. Geissel, H. Irnich, A. Magel, G. Münzenberg, F. Nickel, A. Piechaczek, C. Scheidenberger, W. Schwab, K. Sümmerer, W. Trinder, M. Pfützner, B. Blank, A. Ignatyuk, and G. Kudyaev, Nucl. Phys. **A590**, 785 (1995).

[21] T. Aumann, K. Sümmerer, H. Geissel, B. Blank, T. Brohm, H.-G. Clerc, S. Czajkowski, C. Donzaud, A. Grewe, E. Hanelt, A. Heinz, H. Irnich, M. de Jong, A. Junghans, A. Magel, G. Münzenberg, F. Nickel, M. Pfützner, A. Piechaczek, C. Röhl, C. Scheidenberger, W. Schwab, K.-H. Schmidt, S. Steinhäuser, W. Trinder, and B. Voss, Z. Phys. A **352**, 163 (1995).

[22] G. Gerbier, Ren Guoxiao, and P.B. Price, Phys. Rev. Lett. **60**, 2258 (1988).

[23] W.R. Binns, J.R. Cummings, T.L. Garrard, M.H. Israel, J. Klarmann, E.C. Stone, and C.J. Waddington, Phys. Rev. C **39**, 1785 (1989).

[24] C. Wagemans, *The Nuclear Fission Process* (CRC Press, Boca Raton, FL, 1991).