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**SLOWING DOWN OF RELATIVISTIC HEAVY IONS AND
NEW APPLICATIONS**

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(Invited Talk at the 13.th International Conference Ion Beam Analysis Lisbon, Portugal, August 1997)

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Slowing Down of Relativistic Heavy Ions and New Applications

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Abstract

New precision experiments using powerful accelerator facilities and high-resolution spectrometers have contributed to a better understanding of the atomic and nuclear interactions of relativistic heavy ions with matter. Experimental results on stopping power and energy-loss straggling of bare heavy projectiles demonstrate large systematic deviations from theories based on first order perturbation. The energy-loss straggling is more than a factor of two enhanced for the heaviest projectiles compared to the relativistic Bohr formula. The interaction of cooled relativistic heavy ions with crystals opens up new fields for basic research and applications, i. e., for the first time resonant coherent excitations of both atomic and nuclear levels can be measured at the first harmonic. The spatial monoisotopic separation of exotic nuclei with in-flight separators and the tumor therapy with heavy ions are new applications based on a precise knowledge of slowing down.

1 Introduction

The operation of powerful particle accelerators, storage rings and the developments of new applications have refreshed the motivations to study the interaction of heavy ions penetrating through matter. Although many review articles have been published, e. g. [1, 2, 3], an accurate description based on first principles has not been achieved for the many-body collision processes involving excitation and charge changing of both the target and the projectile atoms. The inherent complexity becomes obvious by considering that at low energies of a few MeV/u, for example, a uranium projectile still carries about 40 electrons during its travel through matter. There are several methods to reduce the complexity of the studies of the atomic heavy-ion interactions: 1. Kinematically complete measurements under single-collision conditions and detection of the emitted photons and electrons in coincidence with the incident and emergent charge states. 2. Interaction under channeling conditions, i. e., strong restriction of the impact parameter range and collisions in a frozen charge state. 3. Studies at relativistic energies where the projectiles are bare or carry only few electrons. Experimental results based on these methods can efficiently contribute to improve the understanding in the field of atomic collisions.

In this contribution modern experimental tools for heavy ions, results on stopping powers, energy straggling, and some new applications like tumor treatment and monoisotopic separation of relativistic exotic nuclei are presented. High-energy heavy ions cooled in a storage ring are a unique potential for channeling experiments to excite coherently atomic and nuclear levels at the first harmonics. Hitherto coherent excitation of nuclear states has not been measured.

2 Experimental

Already from the pioneering experiments on energy loss and charge-changing processes of fission fragments it was concluded that the charge state of the ions during the atomic collisions is the key parameter for a reliable theory [1]. Indeed, the lack of exact knowledge of the projectile charge state during the scattering events is one of the complications with heavy ions compared to light particles like electrons or protons. Fission fragments emitted from an excited nucleus populate a large phase-space volume and emerge in different ionic states, conditions which are not favourable for precise penetration studies. Much progress has been achieved since, due to the application of powerful heavy-ion accelerators. The projectiles provided by accelerators have well defined charge states and are characterized by small longitudinal (momentum spread $\Delta p/p < 10^{-3}$) and transverse emittances ($< 5\pi$ mm mr), i. e., the energy and angular distributions of the accelerated beams are by far superior to the fission fragments. Modern heavy-ion accelerators, like the synchrotron SIS [4], can provide ions of all elements up to uranium with velocities (v) up to $\beta \equiv v/c = 0.9$, where c denotes the velocity of light. The corresponding energy range is sufficient to study atomic collisions with bare ions, a favourable condition which allows a rigorous test of the theory. In figure 1 some high-energy characteristics are presented, e. g., the required kinetic energy to yield a 90 % fraction of bare nuclei for all elements after penetration of Be or Pb targets. The calculations indicate that at relativistic energies Pb

has a superior stripping efficiency in contrast to low energies.

When a relativistic heavy ion travels through matter the atomic interactions are still dominant but the mean free path length for nuclear reactions reaches the order of magnitude of the ranges, i. e., an accurate slowing-down experiment implies a full particle identification with respect to mass and atomic number. Note that at low energies the nuclear reactions are completely negligible for the slowing down of heavy ions. How severely the nuclear interactions can contribute at high energies is shown by calculations indicating the projectile energy corresponding to a 50 % nuclear reaction rate if the ions are implanted in Be or Pb material. Both nucleon-nucleon collisions and the giant resonances due to Coulomb excitation are considered in these calculations.

A further milestone has been reached in the previous years by the operation of heavy-ion storage rings where the highest phase-space densities are achieved by various cooling techniques [5, 6]. In the storage-cooler ring ESR [7, 8] the relative momentum spread of a circulating low-intensity heavy-ion beam can be reduced below 10^{-6} and the emittance below 0.05π mm mr [9].

Besides the accelerator facilities high-resolution devices are needed to measure the energy-loss distribution of heavy ions. Semiconductor detectors are successfully used for spectroscopy of photons and light ions like protons and α -particles. However, when heavy ions are detected in such solid-state detectors, the high ionization density, the dead layer, and the contribution of elastic collisions which do not contribute to the number of free charge carriers cause strong nonlinearities in the response which rule out the use of such detectors for precise energy measurements. Furthermore, the performance of semiconductor detectors is very sensitive to the inevitable radiation damage of the implanted heavy ions.

A solution to this problem is to 'convert' the heavy-ion measurement into an indirect energy measurement by using recoil protons [10] or convoy electrons [11] generated by the heavy-ion beam in well collimated geometry. The use of transverse dispersive magnetic and electrostatic spectrometers has the disadvantage of a too small phase-space acceptance for the broad angular and charge-state distributions of low-energy heavy ions. A very versatile and accurate method for the energy determination of heavy ions is the use of time-of-flight spectrometers consisting of a start and a stop detector. They have been successfully used at low and medium energies up to $\beta \approx 0.2$ [12, 13] and avoid most of the drawbacks of other systems mentioned above. In some cases, e. g., in energy-straggling experiments, it is advantageous that the energy fluctuations of the incident and slowed-down projectiles are measured simultaneously event-by-event to cancel the incident beam properties on the final results. This task can be easily performed by a double-time-of-flight spectrometer [13]. With increasing momenta of the projectiles the resolution of a TOF-spectrometer decreases with the square of the relativistic Lorentz factor $\gamma = (1 - \beta^2)^{-1/2}$. An increase of the path length between start and stop detectors can often not be realized and would in addition require a drastic enlargement of the stop detector to preserve the acceptance.

A high-resolution magnetic spectrometer is an ideal experimental tool to measure the momentum of relativistic heavy ions. The device can still be improved if the ion-optical system is operated as an energy-loss spectrometer [14]. Such a spectrometer allows precise momentum measurements independent of the momentum spread of the

incident beam, i. e., the momentum spread of the projectiles before they interact with the target is canceled in the image at the final focal plane. This can be achieved by two dispersive spectrometer stages with equal momentum resolving powers and the target placed in the dispersive intermediate focal plane. The versatile energy-loss spectrometer FRS [14] at GSI, although mainly designed for separation of nuclear reaction products, has been successfully used for slowing-down measurements of heavy ions up to velocities of $\beta = 0.9$ [15].

Precise measurements of the energy-loss require a major effort but in addition thorough target investigations are needed to obtain reliable results of stopping power and energy straggling. Besides the mean thickness, the chemical purity and the nonuniformity of the targets are critical parameters which can drastically influence the measured energy-loss distribution.

3 Charge states

At low energies of a few MeV/u the lack of precise knowledge of the charge-state population during the atomic interactions of heavy ions with target atoms is one of the main barriers to improve the stopping theories. The concept of effective charges (q_{eff}) [1] and many semiempirical scaling procedures are employed in this velocity regime to provide tabulated values for practical applications [16]. Most of the q_{eff} -scaling procedures are based on the stopping-power ratio of protons, or α -particles, and heavy ions at the same velocity. This treatment has no theoretical justification. Furthermore, the charge state population **inside** the matter is dependent on its density, i. e. on the collision frequency of the ions. This phase effect for the stopping power has been predicted by Bohr and Lindhard [17] and was for the first time experimentally verified at GSI [18] and some years later confirmed by measurements at GANIL [19] using a different experimental method. Note, that a phase effect was also found in the energy loss of H projectiles in Zn targets at very low energies of 20-25 keV [20]. Phase effects and the electron shell structures, both related to the charge states of the projectile and target atoms, complicate inter- and extrapolations to stopping powers of unknown projectile-target combinations at low energies. The situation improves considerably for experiments in higher velocity regions where the projectiles carry only a few electrons [21, 22]. However, to reach such velocities powerful accelerators are needed as demonstrated by the fractional equilibrium yields of bare ions in Be and Pb, as illustrated in figure 2. The curves are calculated by using the cross sections for radiative electron capture (REC), kinematic electron capture (NRC) and ionization. The processes of resonant transfer and excitation (RTE) are only relevant below 100 MeV/u and are not in the scope of the present paper. The projectiles up to Xe are practically bare above 600 MeV/u whereas the heaviest ones, like uranium, require more than 2000 MeV/u.

In general, the theoretical predictions are quite reliable as shown by the comparison with measured data [23]. However, one has to consider that the equilibrium thickness reaches the order of several 100 mg/cm² whereas at about 1 MeV/u less than a few $\mu\text{g}/\text{cm}^2$ are required. This greater target thickness for charge-state equilibrium has to be taken into account for stopping power and energy straggling measurements. However, the

small charge-changing cross sections for relativistic ions have also a remarkable practical advantage: Solid targets for single-collision experiments can be easily prepared. The charge-state evolution in solid Ni targets is presented in figure 3 for 1000 MeV/u Au ions, initially dressed with 10 electrons. The lines are the theoretical predictions [23] for the population of the ionic charge states ranging from 69^+ to 79^+ . The predictions agree well with the data and illustrate that the equilibrium thickness for this projectile-target combination is about 150 mg/cm².

4 Stopping powers and energy-loss straggling

Heavy-ion stopping powers at low energies [24] can be measured with an accuracy of about 5 % where the experimental errors are significantly influenced by the target thickness determination. The thickness measurement of thin (10 – 100 $\mu\text{g}/\text{cm}^2$) self-supporting solid targets is difficult and needs skillful handling in addition to precision instruments [25]. Therefore, the measured energy loss of α -particles and tabulated stopping-power values have been used to deduce the target thickness. In general, reliable experimental data of different groups agree within about 5 % but the agreement with theoretical predictions is much worse and can easily exceed 30 % near the stopping power maximum. It is obvious that precise energy-loss measurements of relativistic heavy ions take more effort than for slow particles, however, the solid target investigations are easier in the relevant thickness range of (100 – 1000) mg/cm².

As demonstrated in the previous section, the charge-exchange processes of relativistic few-electron ions are well understood, which is a basic requirement for the interpretation of the measured stopping-power results. At first glance, one could assume that the stopping power problem for bare heavy ions is readily solved by the relativistic Bethe theory [26]:

$$dE/dx = \frac{4\pi Z_1^2 e^4 N Z_2}{mc^2 \beta^2} \cdot \left(\ln \frac{2mc^2 \beta^2}{I} + \ln \gamma^2 - \beta^2 \right) \quad (1)$$

In this equation $q = Z_1 e$ represents the charge of the projectile moving with velocity v , $N Z_2$ is the density of target electrons, and m and I are the rest mass of the electron and the mean ionization potential of the target atoms, respectively. The term in brackets is the stopping number L .

Already the early experimental work at LBL has indicated that the Bethe theory is not sufficient to describe the data [3]. Those experiments used relativistic heavy ions, but lacking a high-resolution spectrometer, only ranges were measured in solids for a few projectiles at a single incident energy using the track technique in emulsions. The data were interpreted in terms of integrated stopping power formulas based on the Bethe theory with higher-order corrections. The synchrotron SIS in combination with the magnetic spectrometer FRS [14] has allowed direct stopping power measurements in transmission geometry [15]. Representative results are shown in figure 4 for different projectiles in Be at $\beta = 0.84$ as a function of $\frac{\kappa}{2} = \frac{Z_1 \alpha}{\beta}$. Systematic deviations up to 10 % are observed for the heavier projectiles, i. e., only for $\frac{\kappa}{2} \leq 0.2$ the Bethe theory reproduces the data well in this velocity regime. The failure of the relativistic Bethe theory can be explained by shortcomings of the perturbation treatment (first-order Born approximation). In the relativistic velocity regime, where the collisions with the target electrons must be considered

within the framework of the Dirac equation, the Mott cross section has to be used. Furthermore, as shown by Bloch [27] the first-order perturbation theory is not sufficient for small-impact-parameter collisions and a term of $\psi(1) - \text{Re}\psi\left(1 + i\frac{Z_1\alpha}{\beta}\right)$, has to be added to the Bethe theory. Here ψ is the logarithmic derivative of the gamma function. This Bloch term results from a saturation of the momentum transfer in close collisions and has a negative sign, whereas the implementation of the Mott cross section causes an enhanced stopping [15]. A rigorous theory on stopping of bare heavy ions up to ultra-relativistic energies has been developed by Lindhard and Sørensen (LS) [28] based on the Dirac equation. In addition, it takes into account the deviation from scattering off a point-charge in case the de Broglie wave length approaches the size of the projectile nucleus. The results of the LS theory are compared with the experimental data in figure 4 and show excellent agreement. A peculiar result of the 'counteraction' of the Mott and Bloch term is that for each projectile there is a certain velocity where the pure Bethe theory coincides with the LS theory. This interesting behaviour is illustrated in figure 5 for O, Kr, and Au projectiles in Be and Cu targets.

With increasing projectile velocities the de Broglie wave length $\lambda = \frac{h}{p}$ decreases and reaches the size of the nuclear charge distribution, e. g., at about 100 GeV/u this situation is established for Pb ions. The consequence of this characteristics is that in the electron-ion collisions only a part of the ion's charge is probed in contrary to a point-charge model. The correction terms to the first Born approximation of stopping power can be summarized in the change of the stopping number ΔL [28]. In the high-energy limit this term would approach a constant value for a given projectile but due to the effect of the decreasing de Broglie wave length ΔL decreases and goes through zero at about 80 GeV/u, i. e., at ultra-high energies there exists a velocity where the result of the pure Bethe theory again coincides with the LS theory. These features are shown in figure 6 for Pb projectiles. In this presentation ΔL is compared with the experimental data [29, 30]. Experiment and theory are in excellent agreement and particular the deviation from a point charge model is clearly demonstrated. The de Broglie wave length and the size of the nuclear charge are also indicated.

In summary, we have shown that the stopping power for bare relativistic heavy ions is well understood. Experiment and LS theory show excellent agreement over a very large energy region.

The statistical fluctuations of the impact parameters as well as the variation of the transferred momenta in the scattering events causes the width of the energy-loss distribution. The energy-loss straggling, which is defined as the second moment of the energy-loss distribution, is mainly determined by close collisions. At relativistic velocities the energy straggling is completely dominated by violent scattering events of the heavy ions with the target electrons. Therefore, the energy straggling of bare heavy ions should show even stronger deviations from the theoretical descriptions based on first order perturbation than in the case of the stopping power.

The magnitude of the energy transfer Q in the ion-electron collision determines whether the binding energy of the target electrons can be neglected or not [31, 32]. According to

Fano the collisional part of the straggling in first Born approximation reads [32]

$$\Omega_{\text{Fano}}^2 = 4\pi Z_1^2 e^4 N Z_2 \Delta x \cdot \left[\underbrace{\frac{1 - \beta^2/2}{1 - \beta^2}}_{\text{high Q}} + \underbrace{\frac{2 \langle |\sum_j v_j|^2 \rangle_0}{3 Z_2 v^2} \ln \frac{2mv^2}{I_1}}_{\text{low Q}} \right]. \quad (2)$$

Here, I_1 is the mean excitation energy for straggling (see [32]) and $1/2 \cdot m \langle |\sum_j v_j|^2 \rangle_0$ is the mean kinetic energy of a target electron in the ground state. In this equation it is assumed that the heavy ions are completely stripped, $q = Z_1 e$, in the collisions while they penetrate a target of thickness Δx . If the low-Q contribution is neglected the 'relativistic Bohr formula' is retrieved.

At lower velocities, see figure 2, the projectiles are only partially ionized and in addition to the collisional straggling charge-state fluctuations $\Omega_{\text{ch. ex.}}^2$ contribute [33]. The analytical expression for the variance including three charge states reads

$$\Omega_{\text{ch. ex.}}^2 = \frac{\Delta x}{N \cdot \beta^*} \cdot \sum_{i=0}^2 \sum_{j=0}^2 \left[\left(\frac{dE}{dx} \right)_i - \left(\frac{dE}{dx} \right)_j \right]^2 \cdot F_i \cdot (\alpha^* F_j - \sigma_{ij}) \quad (3)$$

where α^* and β^* depend on the charge-exchange cross sections σ_{ij} . The indices i and j denote the number of electrons attached to the projectile before and after a charge-changing collision, respectively, and F and dE/dx are the equilibrium charge-state fraction and the stopping power of ions in a fixed charge state, respectively.

A good knowledge of the electron capture and loss cross sections is needed to calculate the part of the energy-loss straggling caused by charge-state fluctuations. Using the high-energy approximations for the evolution of the charge states, see section above, we can calculate $\Omega_{\text{ch. ex.}}^2$ especially if the projectiles carry only few electrons.

The different contributions to the energy straggling of Kr ions in Be and Pb targets are presented in figure 7. The violent collisions dominate by far the total straggling for Kr ions above 200 MeV/u. The charge-exchange straggling has a smaller influence in the heavier target materials.

The contribution indicated by 'high Q' in the figure 7 is the LS theory [28] discussed above in the context of stopping power. It is now an interesting question how well already the relativistic Bohr formula can reproduce heavy-ion straggling at energies where the charge-changing collisions are rare events. This problem is the pendant to the comparison illustrated with the Bethe theory in the discussion of the stopping powers presented above. The answer is given by the comparison of our experimental results and the LS theory both normalized by the Bohr straggling formula given in equation (2), see figure 8. The experimental data for the interaction of O, Xe, Au, and U projectiles in different target materials [34] are normalized at $\beta = 0.84$. The measurements were done in the velocity range of $0.81 \leq \beta \leq 0.87$ but the normalization is completely negligible compared to the experimental error bars which are dominated by the accuracy of the energy-loss distribution. The comparison reveals that the experimental results can be well reproduced by the LS theory and the data for the heavier projectiles like Au and U are larger by up to a factor of 2.5 compared to the first order perturbation theory represented by

the relativistic Bohr formula. According to the LS theory the deviation is expected to become smaller again, but energy-straggling experiments have not yet been performed in this ultra-relativistic regime and will be a great challenge in the future.

5 New applications

In the previous sections powerful heavy-ion accelerators in combination with high-resolution spectrometers have been employed to yield substantial progress in the understanding of heavy-ion collisions. The atomic interaction within ion-optical systems has been introduced in many fields of research and applications in the last years. A summary of perspectives has been given in ref. [35] and many plans at that time have been successfully realized.

A new generation of experiments has been started with stored and cooled heavy-ion beams in the ESR [7] at GSI. The ions injected into the storage ring interact with a merged cold electron beam (10^8 electrons/cm²) in a straight section of the ESR lattice and due to the ion-electron collisions after each turn the phase-space of the circulating heavy-ion beam is drastically reduced [9]. The relative momentum spread has been reduced below 10^{-6} for low intensity heavy-ion beams and the transverse emittance of the circulating beam is estimated to be 0.05π mm mr. These kinematical properties are ideally suited for channeling experiments with high-energy heavy ions [36, 37]. The interaction of cooled relativistic ions with crystals allows for the first time resonant coherent excitations (RCE) of both atomic and nuclear levels excited at the first harmonic. These investigations are not limited to stable projectiles but as shown recently, also exotic nuclear beams have been stored and cooled in the ESR for precision experiments as well [38, 39, 40]. In the next step towards RCE experiments the cooled beam has to be reinjected into SIS, accelerated to the highest energies, and stochastically extracted without deteriorating the cooled emittances. A new setup for channeling experiments, a UHV vacuum chamber equipped with a goniometer, has already been successfully tested with a channeled beam of 300 MeV/u U^{73+} in a Si crystal along the $\langle 110 \rangle$ axis.

Research and applications with exotic nuclear beams are strongly dependent upon that the interesting reaction products are well separated from all contaminants [41]. An efficient method of separation in flight for relativistic exotic nuclei is based on a precise knowledge of the slowing-down characteristics of heavy ions in shaped degraders placed in a dispersive focal plane of an overall achromatic ion-optical system [14]. The principle of this separation method is shown in figure 9. Using this $B\rho$ - ΔE - $B\rho$ separation technique at the magnetic spectrometer FRS more than 130 new isotopes have been recently discovered including the two doubly magic nuclei ^{100}Sn and ^{78}Ni . A summary of these research activities are given in ref. [42].

The synchrotron SIS can provide heavy-ion beams with ranges of more than 30 cm in water. This gives the opportunity to use the heavy ions for biomedical applications, e. g., for tumor treatment [43]. Heavy ions compared to photons have a superior dose profile for deep seated tumors due to the Bragg peak at the end of their ranges. The range distribution is very narrow in longitudinal and lateral directions. It is obvious, that a successful use of this sharp surgical knife requires a very reliable knowledge of the heavy-

ion penetration through matter. A therapy with ^{12}C ions will be used in first clinical applications at GSI in the near future. A much heavier beam than carbon would cause more problems due to the inevitable nuclear reactions during the implantation in human tissue. The heavy-ion therapy has, besides the favourable dose profile, two more major advantages compared to conventional irradiation: 1. The high ionization density at the end of the range causes a higher biological efficiency (RBE values, defined as the ratio of x-rays doses and particle doses leading to the identical biological effects) in cell damage, 2. a few percent of the therapy beam is fragmented to a positron emitting beam (e. g. ^{11}C) which can be used as a tracer for online control of the implanted profile [44]. A typical example of measured physical and radiobiological effects of a 270 MeV/u C in mammalian cells placed in a water target is illustrated in figure 10 [43, 45]. The slight decrease of the RBE in the plateau of the dose profile is caused by nuclear fragmentation of the projectile beam: the fragments with $Z_1 < 6$ contribute less to the RBE. The irradiation with the ^{12}C beam for an extended target volume has been performed by superposition of many Bragg curves resulting from a variation of the projectile energy and a scanner system consisting of horizontal and vertical deflecting magnets [46]. Conventional therapy projects vary the energy by degraders whereas the new GSI project has the advantage that the synchrotron energy can be changed from pulse-to-pulse. The favourable physical and biological properties of a ^{12}C therapy beam have been successfully demonstrated by irradiation of cells (in vitro) and living animals (in vivo) in very good agreement with a refined track-structure model [47].

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Figure 1: High-energy features of heavy ions interacting with matter [23, 42]. Energies required to yield bare projectiles ($q = Z_1 e$) with a probability of 90 % after penetration of Be and Pb targets (full lines) and maximum energy where only 50 % of the ions survive implantation in Be and Pb materials without nuclear reactions (dashed lines). The dotted line representing Bohr's $\kappa = \frac{2Zv_0}{v}$ for a fixed value of 2 serves for orientation for the applicability of the different theoretical approaches and is a coarse stripping criterion for K-shell electrons. The classical regime is $\kappa \gg 1$ and the validity of perturbation theories $\kappa \ll 1$.

Figure 2: Upper part: Fractional equilibrium yields of fully stripped Xe and U projectiles in Be (solid lines, open circles) and Pb (dashed lines, open squares). The symbols are experimental data obtained at LBL and GSI [23]. Lower part: Calculated equilibrium thicknesses for the charge-state evolution of Xe and U projectiles in Be and Pb targets [23].

Figure 3: The charge-state evolution in solid Ni targets is presented for 1000 MeV/u Au^{69+} ions compared with the theoretical predictions [23] (lines represent 11 charge states).

Figure 4: Experimental stopping powers for different projectiles in Be targets at $\beta = 0.84$ as a function of $\frac{Z_1 \alpha}{\beta}$. The data are compared with the prediction of the LS theory [28] (solid line).

Figure 5: Experimental stopping powers for different projectiles in Be and Cu targets compared to the LS theory [28] (solid lines). The full and open symbols represent data measured at GSI [15] and at GANIL [19], respectively.

Figure 6: The difference of LS and Bethe theory for the stopping number (solid line) is plotted for Pb projectiles as a function of the kinetic energy and compared to the experimental data [29, 30]. The point charge model (dashed line) saturates at about 10 GeV/u. The de Broglie wave length λ (right y-axis) and the size of the nuclear charge are also indicated (dotted line and arrow, respectively).

Figure 7: Calculated contributions to the energy-loss straggling of Kr ions in Be (upper part) and in Pb (lower part) at different energies. The contributions indicated by 'high Q', 'low Q', and 'charge exchange' are calculated according to refs. [28], [32], and [33], respectively (see text).

Figure 8: Experimental energy-straggling values for different projectiles at $\beta = 0.84$ as a function of $\frac{Z_1\alpha}{\beta}$. The data are compared with the prediction of the LS theory [28] (solid line), both are normalized to the relativistic Bohr formula.

Figure 9: Spatial monoisotopic separation of relativistic beams of exotic nuclei by using the slowing-down characteristics in combination with a two-fold magnetic rigidity analysis of an overall achromatic magnetic spectrometer [14].

Figure 10: Cell irradiation with ^{12}C ions at 270 MeV/u with a fluence of $2 \cdot 10^7/\text{cm}^2$ [45]. Upper part: Dose profile in water. Middle part: Measured survival of mammalian cells (CHO) deposited at different positions along the range in a water-phantom. Lower part: Relative biological efficiency (RBE) measured in comparison with 250 keV x-rays.