CONF-8905141--1

(to be presented at the 5th Int'l Conf. on Electrostatic Accelerators and Associated Boosters, Strassbourg, France - May 24-27, 1989, and published in Nucl. Instr. Meth)

ATOMIC PHYSICS USING LARGE ELECTROSTATIC ACCELERATORS

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CONF-8905141--1

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Abstract

This article surveys some areas of atomic physics using large electrostatic accelerators. Brief overviews of ion-atom collisions and ion-solid collisions are followed by a classified listing of recent papers. A single line, correlated electron ion recombination, is chosen to show the recent development of techniques to study various aspects of this phenomenon.

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*Research sponsored by the USDOE, Office of Basic Energy Sciences, Division of Chemical Sciences, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy System, Inc.

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1. Introduction

Studies in atomic collision physics are carried out over a broad range of energies. The energy dependence of many processes (e.g., charge capture, inner shell ionization) has been followed over many orders of magnitude. In fact, one major advantage that electrostatic accelerators hold for these studies is the ease of energy variability.

When I was asked to prepare a paper on the subject of "Atomic Physics with Large Electrostatic Accelerators," the immediate question is "what is meant by 'Large'?" This depends to a great extent on one's point of view. For the atomic physicist, I would say that "large" is anything the size of an EN tandem Van de Graaff or larger. As nuclear installations have gone toward higher energies, a number of EN installations have now fallen into the hands of atomic physicists. These include facilities at Oak Ridge National Laboratory, Aarhus University, and Kansas State University (KSU). It is significant that the Aarhus EN is slated to become an injector into ASTRID, a heavy ion storage ring whose primary purpose is atomic physics and that the KSU tandem has now had a superconducting linac added to it. The breadth of the subject matter which is being investigated is much too large to permit anything but a cursory outline of the types of experiments being carried out. Therefore, I will in the first part of the paper give an overview of some of the recent work and list some recent papers together with their locations to give a flavor of the extent of the work. In the second part, I will pick a single thread, correlated electron-ion recombination, and follow it through the several experimental approaches to it that have evolved in the last few years.

2. Ion-Atom Collisions

The physics of high energy ion-atom collisions has many aspects and is studied using a broad range of projectiles and techniques. With highly charged heavy-ion collisions, a whole range of phenomena can occur. If the ion is of sufficiently high charge, the binding energy match with the electrons in the outer shell of a neutral target atom is such that transfer should take place to high lying n states of the projectile ion. The large field supplied by the highly charged ions also give rise to large release distances and possibility of more than one electron being involved in inelastic collision processes such as charge transfer and ionization. An example of results obtained at the Holifield 25 MV UD facility is shown in fig. 1 for the system U^{q+} (1 MeV/u) + He (q is the ionic charge)[1]. The beam is passed through a gas cell; the projectile ions which have captured an electron ($U^{(q-1)+}$) are measured in coincidence with the charge state of the recoiling target He ion which is measured by a time-of-flight technique. By this means partial cross sections, σ , can be measured. We denote the initial and final charge states of the projectile by subscript and for the target atom by a superscript. Thus $\sigma_{q;1}^0$ denotes single ionization of He, $\sigma_{q;2}^0$ double ionization, $\sigma_{q;q-1}^0$ single charge transfer $\sigma_{q;q-2}^0$ double transfer, and $\sigma_{q;q-1}^0$ is double electron loss by He with only single transfer. This latter process is called transfer ionization (TI); for the case shown, it actually exceeds simple charge transfer and is of greatest interest. It has been shown that for highly charged ions (I, Au, U) in the energy range 0.1 to 1 MeV/u in question that TI involves the transfer of the correlated

electron pair from the He to the U ion, followed by loss of one electron to the continuum. This fact was determined from measurement of the spectrum of electrons occurring at zero degrees with respect to the projectile beam [1]. This experimental approach, which has been dubbed "zero degree electron spectroscopy," has been extensively employed in a number of experiments. Electrons which are released in the projectile ion rest frame appear as a cusp in the laboratory system centered at the electron velocity $v_e = v_i$, the ion velocity (fig. 2). Similarly electrons which are captured to projectile continuum states will appear as a cusp. The difference between capture and loss can be discerned from the shape of the cusp [2], the loss cusp being symmetric and a capture cusp showing higher intensity on the low energy side of the cusp. Low energy projectile Auger electrons will appear on both low and high sides of the cusp corresponding to forward and backward electron ejection. The use of high velocity beams acts as a magnifier [3] (see fig. 2), and when coupled with high resolution electron spectroscopy can yield greatly detailed information on inelastic ion-atom collisions [4].

Another aspect of ion-atom collisions appears when we focus on the target atom which may become multiply ionized in the collision. The detailed mechanism of these multiply ionizing collisions is a subject of great current interest. An example is the work of Schuch et al. [5] who studied the inelasticity of collisions of, e.g.,

The inelasticity, as a function of the number of electrons liberated, was measured using an Elbek magnetic spectrograph and was found to be much

greater than the minimum required for a given degree of ionization. Since it is known that the recoiling target ions carry very little energy (<10 eV), it is established that many "hot" electrons are released in the process. Present studies in this area include impact parameter dependence of the inelasticity and ejected electron energy and angular distributions in coincidence with individual multiple ionization steps.

Remarkably, some of the lowest energy collision studies with multiply charged ions have been made possible using beams formed by multiply ionizing collisions of high energy heavy ions. This is accomplished by extracting the recoil target ions passing them through an electrostatic analyzer and using the resultant low energy multicharged ion beams for further collision studies. In this case, the accelerator beam is used as a "hammer" for producing the ultra-low energy beams [6].

3. Ion-Solid Collisions

As the energy of the ion beam increases, charge capture cross sections decrease rapidly ($\sim v^{-11}$) and once over the maximum ionization cross sections decrease $\sim \alpha(\ln E)/E$ so that solid targets can become "thin" for some processes and "thick" for others. If we consider those bound electrons which have orbital velocities v_e about equal to the ion velocity v_i equilibrium between bound and unbound states will be rapidly established. The statistical interplay between the bound and unbound states is the basis of the "convoy" electron phenomenon. "Convoy" electrons accompany the ion when it exits the foil target. They also appear in a cusp at $v_e = v_i$, and until recently, this was not a very well understood phenomenon. The solution is

derived using statistical arguments to describe the states of outer electrons on ions penetrating solids [7]. This statistical approach has also been successful in explaining the difference in angular momentum distributions of Auger electrons following excitation in gaseous and solid targets [8].

For deeply bound electrons ($v_e \ll v_i$), the solid target may be "thin" and inner-shell vacancy equilibrium may not be attained in these targets. Information on inner-shell ionization processes can thus be obtained from the target thickness dependence of projectile X-ray yields [9].

Experiments on ion channeling in crystalline solids have led to many contributions to both solid state and atomic physics [10]. The one area which I mention here, resonant coherent excitation, is meant to demonstrate the flexibility and precision of electrostatic accelerators. When an ion passes down a channel it experiences a periodic perturbation by the atoms in a crystal row with frequency $\nu = v_i/d$, where d is the atomic spacing in the row. A resonant excitation of the ion can occur when $h(v_i/d)K = \Delta E_{ij}$, where ΔE_{ij} is the energy spacing between states i and j and K is the order of the harmonic ($K = 1, 2, 3 \dots$). We have observed these resonances in a number of systems (e.g., hydrogenic ions) by measuring the charge state distribution emerging from a crystal as a function of ion beam energy. This method depends upon the fact that the ionization cross section of the $2p$ excited state is much larger than that for the $1s$ ground state. An example of data taken at the Holifield is shown in fig. 3 for F^{8+} ions in the second harmonic [11]. The data points are ca 50 keV apart and the figure speaks for itself.

4. Facilities and Programs

To get an overall picture of the field, we list in table 1 the titles and references of a number of recent (1987-1989) papers, representatives of the various branches of the field. At the right of the table, we list the facility at which the work was done.

5. Resonant Electron-Ion Recombination

We will now follow a line of investigation which is currently of great interest and has many manifestations: correlated electron-ion recombination. First, we will consider dielectronic recombination which occurs in electron ion collisions of ions with free electrons. Second, we will examine resonant electron transfer and excitation (RTE) which occurs when an ion collides with an almost free electron weakly bound to an atom. Finally, we will take a brief look at recent studies of dielectronic excitation in crystal channels which have been shown to behave as dense Fermi electron targets.

Much of the interest in this and related processes stems from the desire for a detailed understanding of taking place in hot plasmas such as those found in stellar coronae and controlled fusion devices. In this environment atoms are subject to intense bombardment by electrons whose energy distribution is characterized by the plasma temperature. *Collisions can cause multiple ionization of the atom and the electrons may* also recombine with the ion. The distribution of ion charge states in a plasma at a given temperature depends upon the competing rates of ionization and recombination. When an ion/unbound electron pair recombines the gain in potential energy must be removed in some way. Two processes are known to be

important in recombination: radiative recombination (RR) in which a photon is released whose energy is exactly equal to the potential energy gain, and dielectronic recombination (DR) which is initiated when a continuum electron excites a previously bound electron and in so doing loses just enough energy to be captured itself into a bound state ($n\ell$). The latter process results in a doubly excited ion in the next lower charge state which may either auto-ionize or emit a photon resulting in a stabilized recombination. Thus, for an ion A of charge state q in initial state α the DR process may be written:

It should be noted here that the first step, i.e., the formation of the doubly excited state is the reverse of the Auger process.

Since the DR cross section is made up from a set of resonances and the radiative recombination cross section falls rapidly with increasing relative energy, it is clear that there should be a peak in the energy dependence of the relative importance of DR vis-a-vis RR for a given ionic species. At this time, there has not yet been an actual measurement of radiative recombination for any multiply charged ion. However, one expects that such measurements will be forthcoming from storage rings such as the TSR. Thus far, the measurements of dielectronic recombination in multiply charged ions have been reported in two institutes, both using EN tandem beams. The first results were reported by the ORNL group starting in 1983. The Oak Ridge group uses high velocity multiply charged ion beams merged with a high-density compressed space-charge limited electron beam [12]. The advantages

are that (1) multicharged ions are easily produced at high velocities obtained from, e.g., tandem Van de Graaff accelerators; (2) charge transfer cross sections on background gas for multicharged ions are reduced by ~ 4 orders of magnitude at MeV/nucleon energies compared to keV/nucleon energies; and (3) higher ion velocities require higher energy electron beams and hence higher space charge limited currents and electron target densities. This approach leads to ease of measurement and results for $\Delta n = 0$ collisions have been obtained for eleven ion species [13] extending from B^{2+} to Cl^{6+} .

A schematic of the merged beam apparatus is shown in fig. 4. An ion beam from the ORNL EN Tandem Accelerator enters the interaction region through an axial, 0.64 mm diameter hole in the cathode of the electron gun. It passes through an interaction region 84 cm long. After exiting the interaction region, the ion beam is subjected to charge state analysis. The initial charge state of the ion beam, $q+$ is deflected into a Faraday cup. Ions that have picked up an electron (charge = $(q-1)+$) are deflected onto a solid state position sensitive detector (PSD). (Further details of the experiment are given in ref. [12].) The experimental procedure consisted of optimizing the electron beam, at a particular cathode voltage and counting the $A^{(q-1)+}$ and A^{q+} beams while stepping through the relative energies of interest by changing the energy of the ion beam.

From measurements of resonances that should be very narrow in energy, it was found that the energy resolution in the electron beam was ~ 5 eV. An example of the type of spectra obtained is given in fig. 5 for F^{4+} which is a boron-like ion. For B-like ions, four intermediate doubly excited states

can be formed in the $\Delta n=0$ transition from the ground state

where $X = {}^2D, {}^2S, {}^2P$ or 4P . Since the 4P state requires a spin flip it is not expected to contribute much to the cross section (i.e. $< 5\%$). Similarly the contribution of a metastable beam component via the reaction

is expected to contribute less than 5% even though the metastable beam fraction is ~ 0.5 [14]. This leaves us with contributions from the ${}^2D, {}^2S, {}^2P$ in eqn. (2). These states are written in order of increasing excitation potential. For the 2P doubly excited state two autoionizing channels exist in addition to that indicated in eqn. (3), i.e.

and for the 2S state the additional autoionizing channel to the $1s^2 2s^2 2p^2 \ ^2D$ is open for high $n\ell$ states. The existence of these alternate paths lower the σ_{DR} for these states by an estimated 20% for the 2P and $\sim 10\%$ for 2S for the ions in question.

In fig. 5, we show data for F^{4+} compared with the results of coupled channel calculations for this system [15]. The lower dashed curve is that for zero field, the upper solid curve is multiplied by a "field enhancement" factor for a best fit with the data. This "field enhancement" factor occurs

because of Stark mixing of λ states in the weak (~ 10 V/cm) fields present in the electron beam.

Since the time of the inception of this experiment, merged electron ion beam apparatus with much better energy resolution have been developed. These are the "electron beam cooling" systems now being installed in the various ion storage rings under construction. In these devices, the flat electrode immersed in a magnetic field is used with no compression and the anticipated resolution is in the order of 0.1 eV. At Aarhus University, one of these "coolers" has been placed into a beam line on their EN Tandem Van de Graaff and has been used to measure dielectronic recombination in multicharged carbon and oxygen ions [16] with sufficient resolution to resolve individual n states. In the future, we should anticipate results from storage ring facilities and from larger tandems.

Another experimental method should give a similar and related results involves electron transfer plus excitation (TE). In this case, instead of a truly free electron, we use an atomic target which has weakly bound (almost free) electrons with orbital velocities $v_e \ll v_i$, where v_i is the ion velocity. This process has been dubbed resonant transfer and excitation (RTE) [17]. Here

the doubly excited state can then relax via Auger or radiative decay

Further, the singly excited state can relax with the emission of a second X ray

$$[A^{(q-1)+}(\alpha, n\ell)]^* \rightarrow A^{(q-1)+}(\alpha, \alpha') + h\nu_2. \quad (7)$$

The end results are either an Auger electron which contains information as the $n\ell$ state of originating doubly excited state, or an ion of decreased charge and two photons. Measurements have been made using the Auger electrons (RTEA), measuring charge capture in coincidence with X rays (RTEX) or measuring two X rays in coincidence (RTEXX). In all cases, the relative collision energy is scanned by varying the energy of the ion beam. This often means that several different accelerators are used for a single excitation function. Since this conference is concerned with electrostatic accelerators and associated boosters, I will confine my discussion to work done at these facilities.

An example of the RTEX technique is the experiment on the system

which was studied using the MP Tandem-Linac Facility at Heidelberg [18].

The experimental set up is simple. The ion beam passes through a windowless gas cell into an electrostatic or magnetic charge state analyzer. The Ti K X rays from the collision region are recorded by a Si(Li) detector. The physics of the process is pictured in fig. 6. A K electron is excited and an electron from the target is captured. It is important to note that the resonance is considerably broadened by the momentum distribution (Compton profile) of the electron bound to the hydrogen molecule. The result is shown in fig. 7. The theoretical curve is obtained from a calculation of

the DR cross sections convoluted with the Compton profile of the electron on a hydrogen molecule.

The two X-ray technique (RTEXX) gives additional information concerning the $n\ell$ capture states. This is exemplified in an experiment using S^{15+} ions (70 – 160 MeV) from the Heidelberg facility [19]. Adopting the Auger notation, the KLL reaction is, e.g.,

and the KLM reaction is,

The result of this experiment is shown in fig. 8. The second rise of the K_{α} curve in the region of the higher resonances is caused by cascading from the higher states.

More subtle information concerning the dielectronically doubly excited state is obtained from a study of the Auger decay channel (RTEA). The work referred to here was carried out at the Oak Ridge EN tandem [20]. The experiment utilized the technique of zero degree electron spectroscopy [4] to observe Auger electrons arising from collisions of Li-like O^{5+} with He atoms as a function of energy (5 to 25 MeV) in the region of the KLL resonance. The specific states populated by the dielectronic process are Be-like $1s2s2p^2 \ ^3D$ and the $1s2s2p^2 \ ^1D$. Auger electron spectra taken at varying O^{5+} energies is shown in fig. 9. The rise and decline of the 3D and 1D lines is apparent. The intensities of these lines is plotted versus energy in fig. 10. The curves labeled NTEA represent contributions from the non-resonant contribution to transfer and excitation, i.e., a collision in

which the projectile electron is excited by interaction with the He nucleus followed by an uncorrelated electron capture from the He atom.

Dielectronic excitation processes have now also been studied in crystal channels [21] at ORNL using the 25 MV tandem accelerator at the Holifield Heavy Ion Research Facility. Energetic ions traveling through crystals at small angles to low index directions may be steered to avoid small impact parameter collisions ("channeling") and interact directly only with loosely bound electrons. For ion velocities $v_i \gg v_f$, where v_f is a target Fermi electron velocity representative of the sampled electrons, the penetrating ion may be viewed as being bombarded by a flux of electrons moving at velocity v_i . If this assumption is quantitatively correct, ions traveling through this medium at velocities equivalent to the electron velocities required for sharply varying processes, such as dielectronic or direct excitation of an electron bound to the ion, should experience events similar to those in a hot dense plasma, but with a relatively narrow electron energy distribution, i.e., a Fermi distribution as against a Maxwell-Boltzman distribution at the temperature necessary to carry out these excitation processes.

In vacuum under single collision conditions, the doubly excited state formed by dielectronic excitation would decay either by an Auger process or by radiative stabilization (DR) via two photons. The final result being the production of an ion of reduced charge state and two photons. However, if the state is created in a dense electron medium (i.e., a dense plasma or a crystal channel), secondary collisional processes leading to further excitation and ionization can come into play and may even dominate.

Take as an example of the dielectronic excitation of a hydrogenic ion to a $[2p^2]$ KLL resonance. This state could be collisionally ionized to $[2p]^*$ or it could be excited to a $[2p3\ell]^{**}$ state. The excitation cross section from a given n state to an $(n + 1)$ state is larger than that for direct ionization but the ionization cross sections for high n states are so large that for $n > 3$ in the cases under consideration, the electron can be considered as removed from the ion by either excitation or ionization. The remaining $2p$ electron can then either radiate to $1s$ or undergo a similar collisional excitation or ionization (as would be the case if we had a direct single electron $1s \rightarrow 2p$ excitation).

A summary of most of the reactions which can occur at a KLL resonance is given below.

As an example, we give the results for Ca^{19+} ions (150 – 330 MeV). The Ca^{19+} ion beam passed through the $\langle 110 \rangle$ axis of a 1.2 μm thick silicon crystal. Measurements were made of (a) the emerging charge-state distributions using electrostatic deflection and a solid-state position-sensitive detector, and (b) the X-ray spectra using a Si(Li) detector with a 145 eV resolution at 5.6 keV. With this detector, we are easily able to resolve the $h\nu_1$ ($2p^2 \rightarrow 2p1s$) from $h\nu_2$ ($1s2p \rightarrow 1s^2$), but since $h\nu_1$ and $h\nu_3$ ($2p \rightarrow 1s$), both involve decay to an empty K shell, they cannot be resolved.

In fig. 11, we show for Ca^{19+} the yield of $(h\nu_1 + h\nu_3)$ as a function of ion energy. The features correspond to dielectronic excitation to KLL, KLM, KLN, etc., and at 300 MeV to direct $1s \rightarrow 2p$ excitation. The energies at which these contributions should appear are indicated by the arrows at the bottom of fig. 11a.

The calculated magnitudes of these contributions are obtained from the above rate equations, by assuming rapid substate mixing $n\ell \rightleftharpoons n\ell'$ and then using tabulated radiative and Auger rates. The collisional rates r_i are obtained from $r_i = \sigma_i \rho_e v_i$, where ρ_e is the electron density taken to be $1.9 \times 10^{23} \text{ cm}^{-3}$ for the Si $\langle 110 \rangle$ channel and σ_i is the cross section for considered process. Using the same rate coefficients as those used for the X-ray yields shown in fig. 11a, we can calculate, e.g., the yield of Ca^{20+} ions. (cf. eqn. 11-Vb) and plot it together with the experimental data in fig. 11b. The agreement here is quite good and shows that we have a quantitative understanding of the crystal channel. In the future, one can imagine the study of dielectronic excitation in ions of less well understood structures.

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Figure Captions

Fig. 1. Partial cross sections for charge changing collisions of
of 238 MeV U^{q+} with H as a function of initial charge state.

$$o = \sigma_{q,q}^{0,1}, \bullet = \sigma_{q,q}^{0,2}, \Delta = \sigma_{q,q-1}^{0,1}, \blacktriangle = \sigma_{q,q-1}^{0,2} \quad .$$

Fig. 2. Electron spectrum from 20 MeV Au^{18+} colliding with He observed
at zero degrees. The central peak is at 55 eV ($v_e = v_i$). An
Auger electron with 1 eV in the Au rest frame would appear at a
lab energy of ~ 70 eV.

Fig. 3. Surviving fraction of F^{8+} ions transmitted through a 1600 Å <100>
gold crystal as a function of velocity divided by the resonant
velocity corresponding to the energy for a 1s $\rightarrow$ 2p transition in
vacuum.

Fig. 4. Schematic diagram of the electron-ion merged beam apparatus for
dielectronic recombination measurements (e.g., electron gun
cathode diameter ~ 2 cm, overlap length ~ 84 cm).

Fig. 5. Dielectronic recombination of B-like F^{4+} vs relative electron-ion
collision energy. (The laboratory energy of the F^{4+} is in the
range 1.5 MeV/u.)

Fig. 6. The KLL RTE process for (6 MeV/u) $Ti^{19+} + H_2$.

Fig. 7. Excitation function for Ti $K_{\alpha\beta}$ X rays in coincidence with Ti^{18+} .
The relative contributions for KL_n resonances with $n = 2, 3, 4, 5$ and
>5 are given at their calculated energy positions.

Figure Captions (contd)

Fig. 8. Cross section for the correlated emission of two K X rays as a function of the collision energy: $\bullet$ $K_{\alpha}K_{\alpha}$, $\square$ $K_{\alpha}K_{\beta}$, $\circ$ $K_{\beta}K_{\beta}$...

Fig. 9. Zero degree spectra of Auger electrons emitted from projectile oxygen ions in collision with He as a function of ion beam energy.

Fig. 10. Excitation function for RTE formation of doubly excited $(1s2s2p^2)^3D$ and $(1s2s2p^2)^1D$.

Fig. 11. Dielectronic excitation resonances in Ca^{19+} channeled in 1.2μ $\langle 110 \rangle$ silicon crystal (a) yield of X ray $(h\nu_1 + h\nu_3)$ [see eqn. (11) in text], and (b) yield of Ca^{20+} ions from double ionization of the dielectronically excited state.

TABLE 1

	ACCELERATOR FACILITY
<u>ION-ATOM COLLISIONS</u>	
"State-Selective Observation of Resonant Transfer-Excitation (RTE) in Collisions of F^{6+} with He and H_2 Targets," T.J.M. Zouros et al., Phys. Rev. A (1989), in press	10
"Ion-X-Ray Coincidence Measurements in Heavy Ion Collisions," W. G. Graham et al., Nucl. Instrum. Meth. Phys. Res. B <u>24/25</u> , 69 (1987)	4
"Projectile $1s \rightarrow 2p$ Excitation due to Electron-Electron Interaction in Collisions of O^{5+} and F^{6+} Ions with H_2 and He Targets," T.J.M. Zouros et al., Phys. Rev. Lett. (1989), in press	10
"Unexpected Impact Parameter Dependence in the Angular Distribution of the δ -Electron Production Probability in 0.53 MeV/u $F^{8+} + Ne$," Horst Schmidt-Böcking et al., Phys. Lett. A <u>122</u> , 421 (1987)	10
"Correlated Electron Capture in the Impact Parameter and Final Projectile Charge-State Dependence of ECC Cusp Production in 0.53 MeV $u^{-1} F^{8+} + Ne$," A. Skutlartz et al., J. Phys. B <u>21</u> , 3609 (1988)	10
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"Higher-Order Effects of Electron Capture and Loss to the Continuum in Ion-Atom Collisions," W. Oswald et al., Phys. Rev. Lett. (1989), in press	5
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TABLE 1 (CONTD)

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2. Canberra University - 14 UD
3. Argonne National Laboratory - ATLAS
4. Brookhaven National Laboratory - MP Tandem
5. University of Munich - MP Tandem

6. Heidelberg MPI - MP Tandem
7. Stanford University - FN Tandem
8. Harwell UKEA - EN Tandem
9. ORNL - EN Tandem
10. Kansas State University - EN Tandem

11. Western Michigan University - EN Tandem
12. Aarhus University - EN Tandem
13. Heidelberg MPI - EN Tandem

Fig. 1

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Excitation Function

Fig. 7

Fig. 8

Fig. 10

Fig. 11