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**Investigation of the Particle Selectivity of a Traveling
Potential Wave; Neon Isotope Separation with the
Solitron Process - Final Report**

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Introduction

The general goal was to develop a new source of light isotopes, isotopes such as the mineral isotopes used in nutrition research, based on the new separation concept by Richard F. Post of LLNL (U. S. Patent #5140158, issued August 18, 1992). Much progress was made regarding separation and throughput, concluding that separation works well in conjunction with electrostatic focusing used to obtain enough throughput (enough beam current) to make a practical device.

The next step would likely be a production device, although development of an appropriate metal ion source would be useful (appropriate gas ion sources are commercially available). Funding is an issue; development cost estimates run around two million dollars for a market only several times that cost. Although there is much concern about the future supply of isotopes such as could be produced by the Solitron process, as well as costs, at present the supply from Oak Ridge and Russian sources is adequate for U.S. needs. Should demand grow, these LDRD studies would strongly support proposals for further development of this Solitron process and help assure its likely success. For example, a point design for a magnesium mission was formulated to obtain a consistent set of design numbers that would optimize performance without pushing any constraints seen in these studies. A similar design could be formulated for other missions (magnesium was just a convenient target).

At issue is cost and throughput, with a strong mission dependence. Costs look like dollars per milligram at rates up to some kilograms per year for a 10% natural abundance material, scaling roughly inversely with the natural abundance. But there are large uncertainties. Capital cost is likely to be small but estimated manpower needs run from continuous monitoring to occasional checking. Production rates much higher than kilograms per year are probably best left to bulk processes such as AVLIS and the centrifuge.

Separation Studies

The specific goal of this three year effort was to investigate this novel isotope separation process itself: to determine whether isotopes could indeed be separated and, if so, with what limitations - space charge effects, instabilities, and, in particular, with what throughput limitations.

Termed the Solitron process, the concept is based on the strong isotopic variation in wave/ion interaction for a potential wave passing through an ion beam when the wave speed is near the ion

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speed. The ion's charge-to-mass ratio determines not only which ions are picked up by the wave but also the final energy of those ions that are picked up (accelerated to a higher energy); thus, this method can be used for isotope separation.

In the form studied here, the ion beam passed through a set of electrodes (order 200 rectangular electrodes spaced a cm apart over a 200 cm beam path) and the electrodes were used to drive the potential wave (essentially a half-sinewave, 20 cm in length) along the electrodes, through the ions. Typical values were 400 to 1200 eV for the neon ion beam, a wave velocity 20% faster than the average ion speed, and a peak wave potential (in Volts) order 10% of the ion energy (in eV). In the experiments, the applied wave velocity and amplitude were varied to produce the desired ion/wave interaction.

The principal concern was separation followed closely by throughput concerns. A device was build to study both (initial effort headed by R. F. Post), coupled to analytic efforts. Analytic tools included the DART code (used by Bill Barr) developed at LLNL for magnetic fusion studies and the particle simulation code (implemented by Lou Ann Schwager) developed at UC Berkeley for plasma physics studies. Operation of the device was largely by Lou Ann Schwager.

Because of the large energy gain resulting from the ion/wave interaction and the isotopic dependence of that energy change, current vs. voltage measurements from Faraday cups at the end of the interaction region provided a clear demonstration of isotope separation. Some isotope separation results are given in the paper included below (SPIE Proceedings, Laser Isotope Separation, Los Angeles, Vol. 1859, 244-250, 1993), which includes a discussion of much of the separation principles.

Throughput improvement involves holding the ion beam together against the expansive force of the ion beam's space charge over the wave/ion interaction distance. R.F. Post suggested the use of electrostatic focusing (ESF) for this purpose and DART code calculations showed large current increases were feasible using ESF while maintaining isotope separation. Further, ESF is easy to implement using the same electrodes as are used for driving the wave and lends itself to miniaturization in terms of narrower electrode channels. Indeed, that's what was found experimentally, namely, a 100x current increase over the space charge limited current was obtained on applying ESF with no loss of isotope separation, with another 4x increase obtained by decreasing the electrode channel width from 4 cm to 1 cm (4x in total current increase, 16x increase in current density). The use of a large (e.g. 10 Tesla) uniform magnetic field was ruled out as being not appropriate for our goals. Periodic magnetic focusing was tested experimentally using an array of several hundred ceramic dipole magnets, but periodic electrostatic focusing was clearly superior.

Separation results in the SPIE paper below were taken with electrostatic focusing. Other results have been given at meetings, including a presentation by Lou Ann Schwager to the National Academy of Sciences, at their request, on the Solitron's potential as a new source of isotopes..

Novel wave/ion beam interaction approach to isotope separation

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ABSTRACT

Numerical simulations and experimental studies have been made related to the possibility of employing an externally imposed electrostatic potential wave to separate isotopes. This wave/ion interaction is a selective function of the wave/ion difference velocity and for the appropriate wave amplitude and wave speed, a lighter faster isotope will be reflected by the wave to a higher energy while leaving heavier, slower isotopes virtually undisturbed in energy—allowing subsequent ion separation by simple energy discrimination. In these experiments, a set of some 200 individual electrodes, which surrounded a microamp beam of neon ions, was used to generate the wave. Measurements of the wave amplitudes needed for ion reflection and measurements of the final energies of those reflected ions are consistent with values expected from simple kinetic arguments and with the more detailed results of numeric simulations.

1. INTRODUCTION

A novel method for discriminative particle selection by propagating an electrostatic potential wave through a beam of ions of mixed velocities has been developed. Potential applications of this process are described in the related patent (U.S. Patent No. 5140158), isotope separation being a principal application. Computer simulations of this means of separating isotopes have been made, and experimental demonstrations have been conducted. The principal results of those investigations are reported here; a more detailed paper concerning the concept and demonstrations is in preparation.

The concept is illustrated by the experimental arrangement discussed below and shown schematically in Fig. 1. An ion beam is directed through a set of electrodes to a collector/energy analyzer, here about 200 rectangular (picture-frame in shape) electrodes extending over 260 cm. The electrodes are connected to an external pulse generator for production of the wave that acts on the ion beam. A typical wave shape is a half-sine wave, 13 cm wide (i.e., extending over some 10 electrodes at any instant in time), with a peak amplitude in volts the order of 10% of the ion energy in eV. The wave velocity is typically 10 to 30% faster than the ion velocity. Other means of generating the wave and other wave shapes would be appropriate—the key parameters are the wave velocity and the wave amplitude.

For the wave to pickup the ion, the wave amplitude is required to be larger than the ion kinetic energy in the moving coordinate frame of the wave. A very simple view of the interaction is given by the following kinetic relations. The ion kinetic energy depends on the frame of reference. In the laboratory frame,

$$W_o^I = \frac{1}{2} m_I v_I^2 \quad (1)$$

While in the moving frame of the wave, the ion kinetic energy is less; namely,

$$W_{rel}^I = \frac{1}{2} m_I (\Delta v)^2 \quad (2)$$

Figure 1. Schematic view of the experimental apparatus. An ion beam of some microamps passes through the set of rectangular electrodes (inner dimensions 4 cm by 20 cm) to the collector. Bias voltages on the collector grids allow energy analysis of the resultant ion beam.

where,

m_j	=	ion mass for j^{th} isotope,	
v_j	=	ion velocity in lab coordinates,	
v_{wave}	=	wave velocity in lab coordinates,	
Δv_j	=	wave/ion difference velocity = ion velocity in wave frame.	(3)

Thus, we expect ions to be reflected by the wave when the wave potential is greater than the kinetic energy of an ion in the wave frame; i.e.,

$$\text{ion reflection condition: } \phi > W_{\text{Rel}}^j \quad (4)$$

Furthermore, the velocity gain of reflected ions is twice the ion/wave difference velocity Δv_j . Thus, the expected final kinetic energy of the reflected ions W_o^j is much higher than the initial ion energy; i.e.,

$$\text{is laboratory frame: } W_F^j = \frac{1}{2} m_j (v_j + 2\Delta v_j)^2 W_o^j \quad (5)$$

For a wave velocity not much faster than the ion velocity, the kinetic energy of an ion in the wave frame is small, arbitrarily small if one considers wave speeds approaching the ion speed. For a monoenergetic beam, two different isotopes having two different speeds will have the same kinetic energy in

the lab frame but very different kinetic energies in the wave frame. It is this large difference in wave frame kinetic energy that is the basis for the separation scheme considered here. By regulating the velocity and amplitude of this traveling electric potential wave, lighter ions can be selectively accelerated to nearly double the beam energy while leaving the heavier ions relatively unaffected in energy, allowing subsequent separation and collection by simple energy filtering. Similar arguments apply to a wave traveling slower than the ions, except then the heavier ions are decelerated by the wave and it is the lighter ions that remain at the initial energy.

For the neon example considered below, Ne^{20} and Ne^{22} wave frame kinetic energies differ by 50 to 100% (Ne^{22} being the larger of the two). This energy difference is much larger than any inaccuracies or spatial variations in the wave amplitude and, therefore, it is easy to tune the wave amplitude so as to pick up the Ne^{20} without picking up the Ne^{22} . Examples to this neon separation process are shown below.

All conclusions stated below are based on measurements of ion currents and energy analysis of those ion currents. In the future, we hope to have sufficient baffling/pumping of background gas to allow direct RGA analysis of the ion stream.

2. COMPUTER SIMULATION DEMONSTRATION

Particle simulations have been used to help further understand this separation process. The particle simulation shown in Fig. 2 provides a good illustration of neon separation. Neon has two principal isotopes, Ne^{20} (91%) and Ne^{22} (9%). The beam energy for the simulation is 400 eV, corresponding to velocities of 62.1 and 59.2 km/s for Ne^{20} and Ne^{22} , respectively. The wave—approximately a half-sine wave positive potential pulse, 10 cm wide—has a velocity of 78 km/s, 25 to 30% faster than the ion velocities. Thus, the ion kinetic energies relative to the wave are 26 and 40 eV for the Ne^{20} and Ne^{22} , respectively, and a wave potential greater than 26 V would be needed to pick up the Ne^{20} and greater than 40 V for Ne^{22} . For the simulation shown in Fig. 2, the peak wave amplitude was 34 volts, about midway between the Ne^{20} and Ne^{22} wave-frame kinetic energies. Thus, we expect the heavier isotope to pass through the wave while the lighter ion reflects off the wave, as seen in the simulation.

The simulation shown in Fig. 2 is a snapshot of the ion locations and velocities after the wave has moved about 2/3 the way towards the collector; i.e., 22 μs after the wave has been launched. The group of lower velocity ions in the center of the figure form a good marker; they correspond to ions that entered near $t = 0$ coincidentally with the wave. Ions to the left of those initial ions are those that entered subsequently to the launching of the wave and have just the 400 eV velocities. Ions to the right of those initial ions have been processed by the wave. As shown, there are no Ne^{20} ions behind the wave, only the heavier Ne^{22} ions. Those Ne^{20} ions have been swept in front of the wave, and have a much higher velocity—higher by twice the wave/ Ne^{20} difference velocity. The heavier Ne^{22} ions suffer a small forward kick as they pass through the wave but are otherwise unaffected as shown. Ions shown to the right of the wave are ions yet to be processed by the wave.

Figure 2. Velocity/position map from a 1-D particle-in-cell simulation of the separation of 400 eV neon ions. Each "dot" in the figure represents the position and velocity of ions within the separation region 22 microseconds after the wave was launched.

3. EXPERIMENTAL DEMONSTRATION

3.1. Experimental facility

An experimental test of the concept was developed, using a commercial ion source and a set of electrodes convenient for producing the wave by using external electronics to sequentially pulse the electrodes. A four-meter vacuum system was built, comprised of a source region, a wave separation region, and a collection/analysis region. This arrangement is the one shown schematically in Fig. 1. The 200 electrodes are rectangular in shape, 4 cm by 20 cm inner dimensions, 1 cm in width, and extend over a length of 260 cm. A commercial ion gun followed by skimmer plates biased to remove electrons is used to produce a nearly monoenergetic beam of neon ions passing through the electrodes to the collector/energy analyzer. The slot width in the skimmer plates is 1 cm by 10 cm, smaller than the 4 cm by 20 cm channel formed by the electrodes, resulting in approximately a 1 microamp beam of neon ions, as limited by space charge.

The wave was formed by sequentially pulsing each of the 200 electrodes with a half-sine wave pulse of amplitude Φ and duration Δt . The wave speed is simply determined by the electrode spacing and the time delay between pulses. The width of the wave is determined by the ratio of individual pulse width Δt to the time delay between pulses, typically a factor of 10 to 15. The peak wave amplitude is the individual pulse peak amplitude Φ . Thus, at any instant in time, some 10 to 15 electrodes are at voltage, forming a half-sine wave potential pulse of peak potential Φ ; neighboring electrodes are at ground potential, with this wave shape propagating at a speed v_{wave} , based on the sequencing frequency of the individual electrode pulses.

Waves were continuously launched so as to process most of the dc ion beam. Typically, the launching of a new wave was triggered as the present wave passed the 100th electrode, such that there were always two waves present in the 200 electrode device at any one time (spaced 100 electrodes apart and therefore not interacting).

Energy analysis of the exiting beam current was done with a set of gridded electrodes in front of a Faraday cup collector at the end of the 200 electrodes; i.e., for a collector voltage V , the beam current measured is comprised only of those ions whose energy in eV is greater than V .

3.2. Measurement of onset voltages

The plots of ion signal vs wave potential is shown in Fig. 3 for three different wave velocities. The ion signals demonstrate the variation in the wave amplitude required to pick up Ne^{20} as a function of wave velocity. For this data the ion energy was 400 eV and the collector voltage was set at 800 volts, a collector voltage high enough to repel the main ion beam but low enough to allow collection of ions reflected by the wave (as seen below from the corresponding energy spectrum of the extracted ions). For each curve, the wave velocity was set at the indicated value and the wave potential was varied from 0 to 100 V.

Figure 3. Measurements of minimum wave potential needed for ion reflection for three wave velocities in a 400 eV neon ion beam. The collector voltage was 800 V, 2x the initial beam energy, but less than the expected final energy of ions picked up by the wave.

The kinetic energy of the 400 eV (lab frame) Ne^{20} ions in the (78, 82, and 87 km/s) moving wave frames are 26, 41, and 64 eV, respectively. Indeed, those (denoted W_e^{20} in the figure) are very nearly the onset values seen in Fig. 3. The small additional delay in the onset and the following peak structure is also seen in computational modeling of this interaction and results from spatial sag in the wave potential across the 4 cm width of the electrode channel and associated focusing effects.

Most of the ions measured are Ne^{20} ; approximately a 50% higher wave potential is needed to pick up the Ne^{22} . The small bumps at 57 and 82 V in the 78 and 82 km/s curves of Fig. 3 are due to Ne^{22} extraction, as discussed below (Ne^{22} assay is 9% vs 91% for Ne^{20}).

3.3. Measurement of final/extraction energies

The energy spectrums corresponding to the peak of the ion signals in Fig. 3 are shown in Fig. 4. The expected (theory) final velocity is the initial value, plus twice the wave/ion difference velocity (independent of the wave amplitude), typically corresponding to an energy nearly twice the initial beam energy. To obtain the energy spectrums shown in Fig. 4, the wave potential was held constant at the values corresponding to the peak ion signals in Fig. 3 and the collector voltage was varied from 0 to 1500 volts. The final energies expected from the relations above are 915, 1080, and 1300 eV for the 78, 82 and 87 km/s wave velocities, respectively. Including a 6% collector correction due to finite grid spacing, the measured final values are in good agreement with the expected final energies as indicated by the arrows.

Figure 4. Energy spectrums of extracted Ne^{20} ions corresponding to Fig. 3.

4. CONCLUSIONS

Numerical simulations and experimental studies have demonstrated the possibility of employing an externally imposed electrostatic potential wave on an ion beam to separate isotopes. This wave/ion interaction has been found to be a sensitive function of the wave/ion difference velocity. For the appropriate wave amplitude and wave speed the lighter isotope is reflected by the wave to a higher energy while leaving the heavier isotope virtually undisturbed in energy. Subsequently, ion separation by simple energy discrimination is easily achieved. We found, in agreement with theory, that the energy of the reflected ion is nearly twice that of the original beam.

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