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A linear mass spectrometer by induced Hall potential for electromagnetic isotopic separation working at high pressures

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ABSTRACT

In this paper a novel alternative for bulk electromagnetic separation working at high pressures is proposed. It is shown that if a self-induced Hall potential is stimulated in the boundaries, the system will be able to take advantage of the collisions process, boosting the isotopic separation and resulting in a linear-spectrometer with a higher spatial separation per unit length than a traditional calutron. Although originally the concept was devised for the production of medical isotopes where the minority isotope to be separated is produced by neutron capture and is the heavier isotope, if the Hall potential is replaced by an external electrical field, the concept is equally applicable for situations where the minority isotope is the lighter one, as for example in the enrichment of uranium. Additional R&D is required to explore further the possibilities of this concept and to identify optimal values for several of the system design variables.

1. Introduction

Since the late 1940's the dominant source of most of the enriched stable isotopes produced in the United States has been calutrons. These large separators were originally developed to separate the isotopes of uranium in World War II. The technology that they employ, which has been relatively unchanged for the last 50 years, is based on the electromagnetic separation of elemental material into its constituents (Adelstein and Manning, 1995).

Nevertheless, despite the robustness and simplicity of calutrons, they are very inefficient in terms of processed material but very efficient in terms of product purity. For example, the plasma separation process that has been developed in recent years at the Oak Ridge National Laboratory (ORNL) is only about half as efficient as the process performed by calutrons in terms of product purity, but because a calutron only works at very low pressures (a millionth of an atmosphere) the plasma separation process is 300 times faster (Eerkens, 2006).

In an attempt to improve the very low throughput of calutrons, the Department of Engineering at the University of Cambridge is developing an alternative approach which facilitates higher concentrations of material, i.e. higher pressure working, while at the same time maintaining the robustness and reliability of a calutron. Additionally it will be also demonstrated that the spatial-power separation of the proposed concept is at least 5 times higher than that of a classical calutron, which translates into smaller dimensions than traditional calutrons.

The idea proposed results in a linear spectrograph boosted by an induced Hall potential. In this initial paper, the theory behind this concept is outlined for the first time.

2. Electromagnetic isotopic separation boosted by an induced Hall potential

2.1. Statement of concept

Fig. 1 presents a sketch of a classical calutron and Figs. 2 and 3 show the proposed linear mass spectrometer, which will be explained below (see Fig. 4).

For the sake of illustration, let assume there are only two isotopes to be separated, and also let us assume that the majority isotope has a mass m_1 and the minority isotope a mass m_1 with $m_1 < m_2$. This assumption is certainly valid for many significant radioisotopes in nuclear medicine, for example, the important radioisotope ^{99}Mo, which is produced by the neutronic irradiation of stable molybdenum. In general, this assumption holds true for

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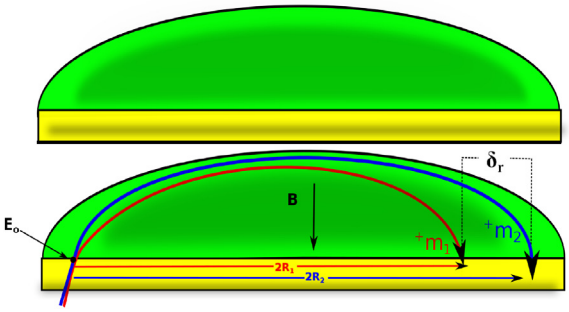

Fig. 1. Sketch of a classical calutron mass spectrograph.

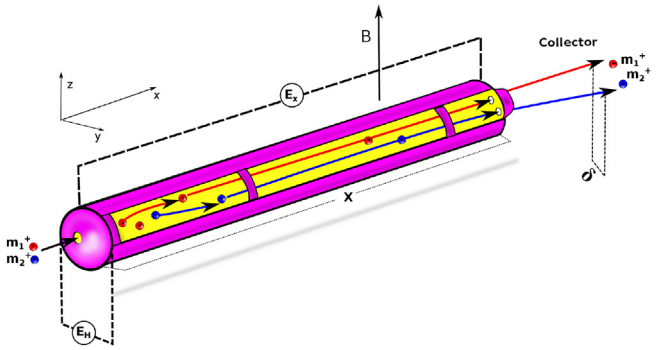

Fig. 2. The proposed linear mass spectrometer for bulk-isotopic electromagnetic separation.

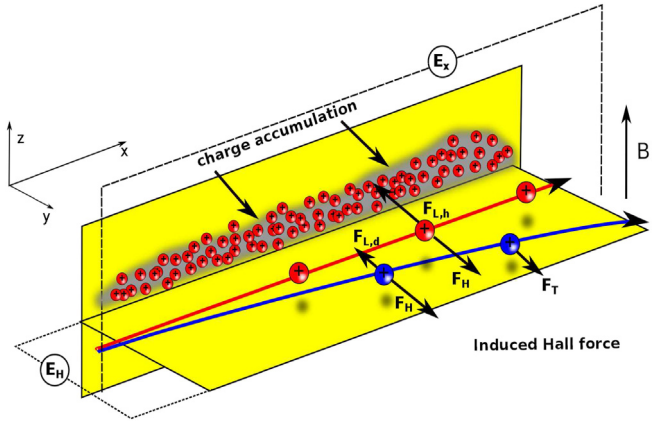

Fig. 3. The Lorentz force on the lighter and more abundant isotope m_1 is exactly compensated by the induced Hall force; however, this is not the case for the heavier isotope m_2.

radioisotopes arising from neutronic irradiation as

$$A + n \rightarrow B \tag{1}$$

where isotope A is the element irradiated, say, in a nuclear reactor, and isotope B is the desired isotope which is gaining one or more neutrons, so that the condition $m_1 < m_2$ is satisfied. However, even if this condition does not apply, for example, for uranium enrichment where the desired isotope ^{235}U is lighter than the bulk isotope ^{238}U, it is still possible to apply the proposed concept, see the Appendix.

First of all, referring to Figs. 2 and 3, before we apply the

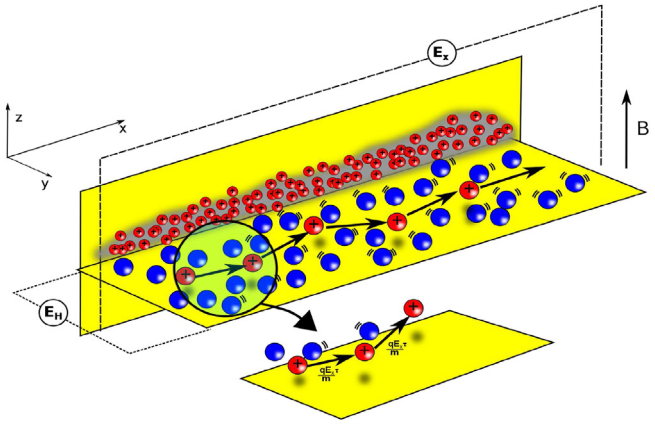

Fig. 4. As a result of the collisions process and the external longitudinal electrical field applied, a drift velocity, Δv_x, is developed.

electrical field E_x the ions of the heavier isotope m_2 and lighter isotope m_1, as well as the neutral atoms (non-ionized), are moving randomly due to their thermal kinetic energy, so their average velocity is zero. Under the effect of the longitudinal electric field E_x, ions will move in the direction of the applied force (see Fig. 3) with a drift velocity Δv_x which is, in general, much slower than the mean thermal velocity. The drift velocity is the maximum velocity attained by the ions between collisions (see Fig. 3).

The longitudinal acceleration acting on ion i is given by

$$a_{x,i} = \frac{q\mathbf{E}_x}{m_i} \tag{2}$$

where q is the ion's charge, so the drift velocity of the ion is approximately given by

$$\Delta v_{x,i} = \frac{q\mathbf{E}_x}{m_i}\tau_i \tag{3}$$

where τ_i is the mean free time between collisions. According to kinetic theory, the mean free time τ_i is related to the microscopic scattering cross-section σ and the number density of ions/atoms N_g by

$$\tau_i \cong \frac{1}{N_g \sigma v_{x,i}} \tag{4}$$

where

$$\frac{1}{2}m_i v_{x,i}^2 = \overline{e} = \frac{3}{2}\kappa T \tag{5}$$

is the mean thermal kinetic energy, with κ being the Boltzmann constant and T the mean temperature of the gas.

Now, in the presence of a magnetic field $\mathbf{B}$, there will be a time-averaged magnetic force given by the Lorentz force equation

$$F_{i,y}^L = q\Delta v_{x,i}\mathbf{B}_z \tag{6}$$

and inserting the drift velocity expression in Eq. (4) yields

$$F_{i,y}^L = -\frac{q^2 E_x \tau_i \mathbf{B}_z}{m_i} \tag{7}$$

Now, because of boundary confinement, an accumulation of charges will result, so that the net current in the y-direction is zero.