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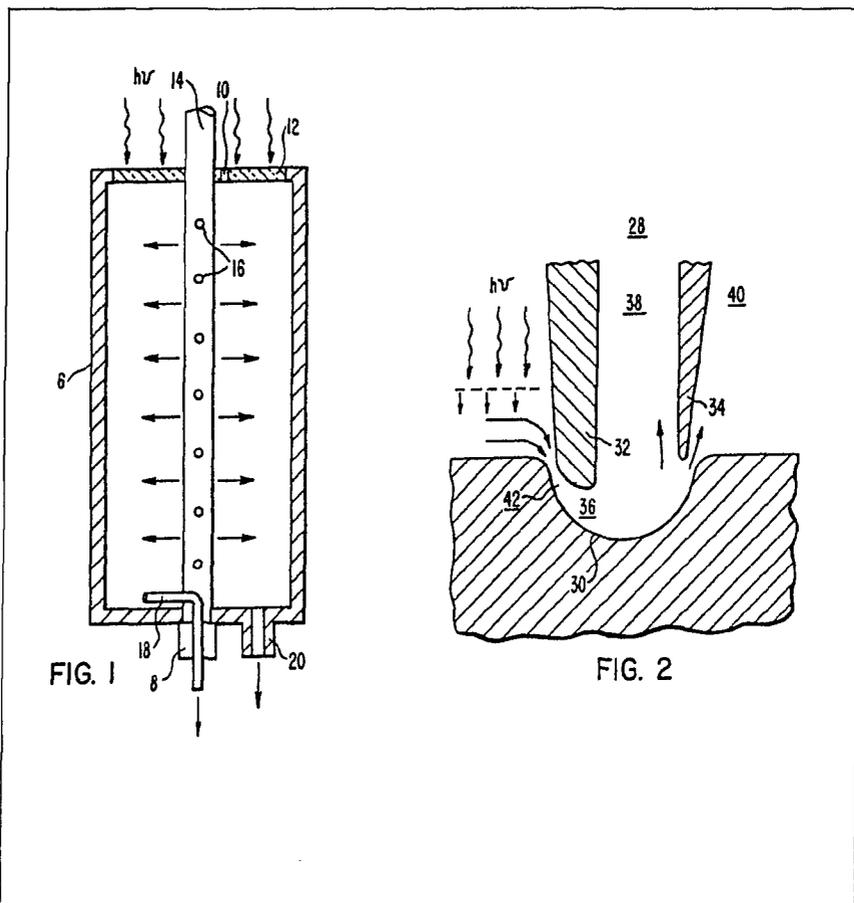
(54) Isotopic Separation

(57) Isotopic species in an isotopic mixture including a first species having a first isotope and a second species having a second isotope are separated by selectively exciting the first species in preference to the second species and then reacting the selectively excited first species with an additional pre-selected radiation, an electron or another chemical species so as to form a product having a mass different from the original first species and separating the product from the balance of the

mixture in a centrifugal separating device such as a centrifuge (Fig. 1) or aerodynamic nozzle (Fig. 2).

In the centrifuge (Fig. 1), the isotopic mixture is passed via 14 and 16 into rotor 6 where it is irradiated through window 12. Heavier and lighter components are withdrawn via 18 and 20 respectively.

In Figure 2 the irradiated mixture experiences a large centrifugal force while passing through neck area 42 and is separated in deflection area 36 into lighter 38 and heavier 40 components.



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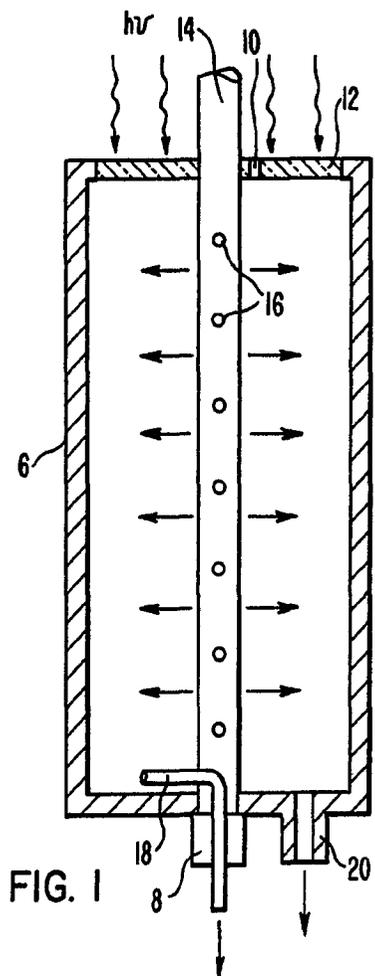


FIG. 1

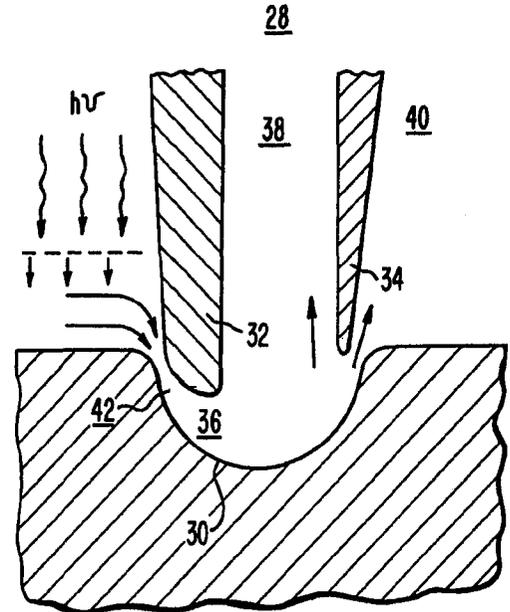


FIG. 2

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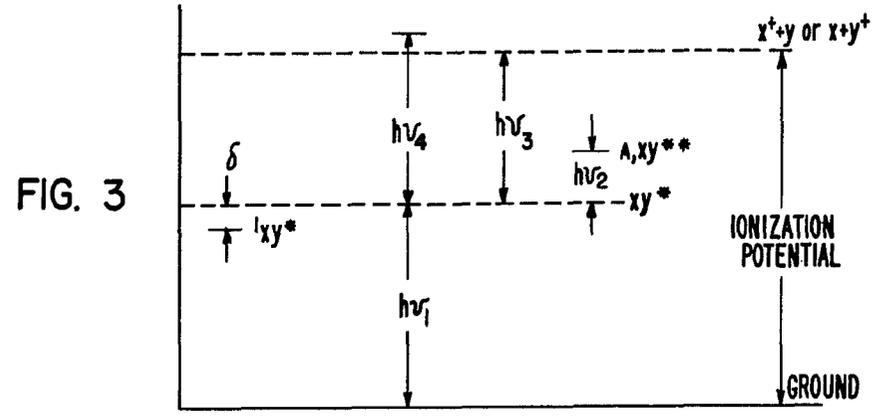


FIG. 3

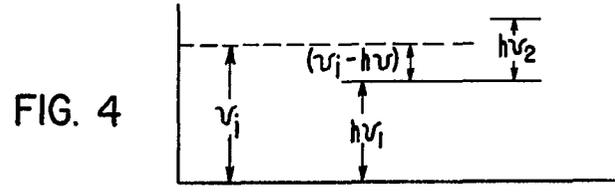


FIG. 4

SPECIFICATION

Isotopic Separation

- 5 The present invention relates to mass isotopic separation and more particularly provides a separation method based upon mass differences enhanced by photo-irradiation. 5
- Selection isotopic species are useful for many purposes including medical apparatus and treatment, tracer studies of chemical and biological processes, and as target materials and fuels for nuclear reactor application. Perhaps the largest present utilization is for nuclear reactors, which typically require, for
- 10 example, fuel enriched in Uranium-235. 10
- The system most widely used today for isotopic separation is gaseous diffusion, which requires a large, complex, and costly cascading network. More recently systems are being considered based upon technologies such as distillation and photo-ionization in the presence of magnetic and electric fields. Exemplary of the latter are U.S. Patent No. 3,772,519 in the name of R.H. Levy et al and U.S. Patent No.
- 15 3,433,087 in the name of J. Robieux et al. 15
- Centrifugal separation of isotopes has also been considered, but this again requires a large number of centrifuges in order to obtain the desired results.
- It is therefore the principal object of the present invention to provide an efficient isotopic separation process, that is, a process which does not require the large amount of separation equipment needed by
- 20 today's processes. 20
- With this object in view, the present invention resides in a method for separating isotopic species in an isotopic mixture including a first species having a first isotope and a second species having a second isotope, wherein said first species is selectively excited in preference to said second species, characterized in that said selectively excited first species is then reacted with one of an electron, a preselected radiation and a
- 25 chemical species so as to form a product including said first species which product has a mass different from said second species by a larger degree than said original first species; and said mixture is conducted through a centrifugal separating device wherein, as a result of the enhanced difference in mass, said product is separated from the balance of said mixture and follows a path different from the flow path of the balance of said mixture, both flow paths terminating in different outlets (38, 40). 25
- 30 The present invention is based upon the principle that the isotope separation factor of a mass separation device, such as a gas centrifuge or an aerodynamic nozzle, is enhanced when the mass difference among isotopic species is made larger within the nozzle or rotor region. 30
- The species is excited and, in the excited state, can preferentially be made to undergo a selective reaction which results in a product containing the particular isotope, and having a mass which is much
- 35 different from that of the original isotopic species which mass difference then is utilized to separate the desired product from the mixture. 35
- In one embodiment the mass differential is increased through a photo-selective dissociative electron attachment reaction. The mixture, including the selectively excited species, is exposed to free electrons with proper energies such that the selectively excited molecular species undergo dissociation after elec-
- 40 tron attachment. The product negative ion is of smaller mass than the original isotopic species, and hence is more easily separated from the mixture by methods dependent upon the mass of the species. 40
- In another embodiment the mass difference is increased through multi-step selective dissociative ionization. Subsequent to placing the desired isotopic species in an excited state, it is further selectively irradiated, such as in a selected field, beyond the ionization and dissociation limited, so that a free elec-
- 45 tron and a neutral fragment are released from the molecule. The remaining product is a positive ion of different mass than the original species, and either the neutral fragment or the ion contains the particular desired isotope. 45
- Another embodiment is the combination of the two processes thus described. A selected compound in a mixture under selective irradiation has constituents which can undergo either of the above processes.
- 50 Here, the photo-electrons released from the multi-step selective dissociative ionization reaction are in the proper energy range such that photo-selective dissociative electron attachment can be brought about with the selectively excited isotopic species. Therefore, the productions include positive and negative ions of the same isotopic species. These ions may then react together forming neutral molecules as the final product. These product molecules, having smaller than original mass, represent an increase in the
- 55 original isotopic mass difference, and are accordingly more easily separated from the balance of the mixture. 55
- In yet another embodiment the selectively excited species is made to undergo a preferential chemical reaction with a reactant to form a chemical compound containing the selected isotopic species. The product has a different mass than the original isotopic species, and is accordingly easily separated based
- 60 upon the increased mass differential. 60
- It will be apparent to those skilled in the art that the various steps of the inventive method are not completely efficient. Accordingly, it is to be understood that reference to the term "separation" and the like refer to increasing the concentration of the selected isotope as compared to the feed concentration.
- The invention will become more readily apparent from the following description, of a preferred embodi-
- 65 ment thereof shown, by way of example only, in the accompanying drawings, in which: 65

Figure 1 is a schematic of a rotor application in accordance with this invention;
 Figure 2 is a schematic of a high velocity nozzle application of this invention;
 Figure 3 is a schematic representation of photo-excitation processes; and
 Figure 4 is another schematic representation of photo-excitation processes.

Atomic and molecular species of differing mass can be separated by centrifugal force so that the heavier species traverse one preferred flow path, while the lighter species traverse another. Once different preferred flow paths or locations are established for different species, separate collection is relatively simple.

Two of many types of mass separation devices are simply illustrated in Figures 1 and 2. It is to be understood that the invention is not limited to the two devices exemplified. Figure 1 shows a rotor 6 which is driven by means such as a motor 8 at a high rotational velocity. The rotor 6 includes an inlet 14 through which a mixture to be separated, preferably gaseous, enters the rotor 6. Electrons, in accordance with some embodiments of this invention, can also be injected through the inlet 14 or through other inlet means 10. The inlet 14 also includes means for discharging the mixture or other particles or species within the rotor, such as perforations 16. The rotor in accordance with this invention can also include a transparent surface, such as the window 12 for injection of photon irradiation discussed hereafter. By virtue of the high angular velocity of the rotor 6, the mixture experiences a centrifugal force such that the heavier species tend to aggregate and have a higher concentration near the outer periphery of the rotor, while lighter species tend to congregate near the center of the rotor. Accordingly, the heavy species can be discharged through an outlet 18 near the periphery of the rotor, and the lighter species through outlet 20 closer to the center of the rotor. Figure 2 illustrates the nozzle region 28 of a centrifuge. By virtue of the curved surface of a deflector 30 and the relative positioning of prongs 32, 34, species entering a deflection region 36 are discharged through outlet 38 or outlet 40. The species experience a large centrifugal force as a jet stream passing through a neck area 42, with the heavier species follow a path in preference to outlet 40 and the lighter particles following a preferential path to outlet 38.

An isotope separation factor (S) for such systems can be shown to be

$$S = \left[\exp \frac{\Delta M v^2}{2RT} - 1 \right]$$

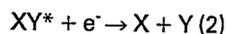
where ΔM is the difference in molecular weight of two isotopic species, v is the peripheral velocity of the rotor or the expanding jet velocity, R is the universal gas constant, and T is the absolute temperature of the gaseous mixture. For an exemplary separation of Uranium-235 from Uranium-238 where $v = 2.0 \times 10^4$ cm/sec, $T = 333K$, and $\Delta M = 3$, the separation factor $S = 2.24 \times 10^{-2}$.

From Equation (1) it can be seen that the separation factor can be increased if the mass difference, ΔM , is increased.

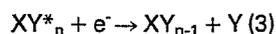
An increase in the mass difference can be effected in several manners based upon selective photoexcitation. Figure 3 illustrates, in simplified fashion, selective photo-excitation processes. Additional detail of such processes is provided in the above-mentioned Levy et al patent, and will only be briefly summarized herein. Figure 3 illustrates that molecular or atomic species can exist in different energy states, including the ground state and the excited states including rotational, vibrational and/or electronic excitation. In the Figure, an isotopic shift of δ is shown for the absorption spectra between compound XY and 1XY wherein X and 1X represent different isotopes of a given element, and Y represents a different element or compound in the molecule XY. Figure 3 also shows that XY can be selectively excited in preference to 1XY , from the ground state to a preselected excited state, represented as XY*, by addition of energy via absorption of radiation $h\nu_1$, where ν_1 is the preselected radiation frequency and h is the Planck constant. While multiple excited states exist, such as state "A" in Figure 3 which can be achieved through further selected irradiation of XY* with $h\nu_2$ (to a state represented as XY**), the Figure also shows that XY* can also be selectively raised to its dissociative ionization threshold by selective addition of $h\nu_3$, or above the threshold by $h\nu_4$. Upon reaching the dissociative ionization state, an electron is ejected, and positive ion X⁺ (or Y⁺) and neutral fragment Y (or X) are formed.

In all of the embodiments disclosed herein, a selected isotopic species is initially preferentially excited by narrow band radiation at a predetermined wavelength.

In one embodiment, the selectively excited XY* is exposed to and hence reacted with free electrons (e⁻), such that a negative ion containing the particular isotope X is formed. This dissociative electron attachment reaction can be represented as:



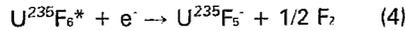
or



It is known that the reactions (2) and (3) have a cross-section which increases strongly with the degree of

internal excitation of XY. Hence, selective photo-excitation of gaseous molecules in conjunction with reactions with electrons having appropriate energy will produce $X^+ + Y$ in preference to ${}^1X + Y$, or $XY_{n-1} + Y$ in preference to ${}^1XY_{n-1} + Y$.

An exemplary process based upon a mixture containing $U^{235}F_6$ and $U^{238}F_6$ (uranium hexafluoride) can be described as:



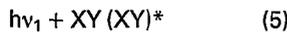
The mixture, subsequent to reaction (4), includes $U^{238}F_6$, some unreacted $U^{235}F_6$, free fluorine and electrons, and the newly formed $U^{235}F_5^-$. It is evident that the mass of the $U^{235}F_5^-$ is different than the balance of constituents of the mixture, and, in accordance with the invention, can be separated accordingly. It will also be noted that through charge exchange reactions, for example, $UF_5 + UF_6 \rightarrow UF_5 + UF_6$ may convert to the neutral species UF_5 . This charge exchange does not, however, substantially affect the increased mass differential which is the key factor for improved isotope separation.

The exemplary reaction (4) has a threshold of about 1 eV at room temperature, and rises to a peak at about 2 eV. Accordingly, the electrons should have an energy less than 1 eV to avoid reaction with ground state $U^{238}F_6$ molecules. The separation factor S for the exemplary reaction, where $\Delta M = 22$ (between $U^{238}F_6$ and $U^{235}F_6$), $v = 2.0 \times 10^4$ cm/sec, and $T = 333K$, is:

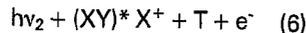
$$S = \exp \left[\frac{(22)(2.0 \times 10^4)^2}{2(8.32 \times 10^7) 333} \right] - 1 = 0.172$$

which represents a gain of a factor of 8 over the prior art type system exemplified above.

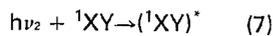
In another embodiment selective, step-wise absorption is utilized to form a positive ion. The above mentioned Robieux et al patent teaches irradiating an isotopic mixture with two light beams, one of which is ultraviolet. The first beam, $h\nu_1$, is preferably highly monochromatic for selective excitation:



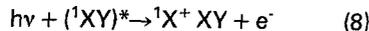
and the second beam provides energy to dissociatively ionize the $(XY)^*$, i.e.,



With reference to Figure 4, it has been found highly desirable to add the additional constraint to the Robieux et al teaching that $(V_1 - h\nu_1)h\nu_2 > V_1$, where V_1 is the ionization potential of the reaction $XY \rightarrow X^+ + Y + e^-$. This constraint permits step-wise ionization of the undesired isotopic species by $h\nu_2$. It does not, however, preclude step-wise ionization of an undesired species according to:

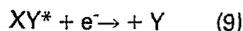


and

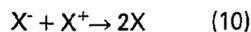


where 1X in reactions (7) and (8) is another isotope of X in reactions (5) and (6). This non-selective parallel occurring ionization mechanism is likely to defeat the intent of the selective ionization unless $h\nu_2$ is further constrained to be a wavelength to which 1XY is transparent. Alternatively, both $h\nu_1$ and $h\nu_2$ can be highly monochromatic so as to be selectively absorbed by XY only.

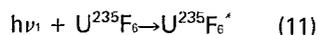
A further improvement can be achieved by selecting $h\nu_1$ and $h\nu_2$ such that, in addition to the constraints set forth above, the electron production in reaction (6) can be made to have suitable energy to be selectively and dissociatively attached to XY^* . A dissociative electron attachment process has a lower threshold and a larger cross-section for an internally excited species than for a normal species. Therefore, for an electronegative gas such as, for example, UF_6 , the following selective processes are highly possible:



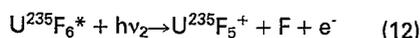
and



Accordingly with respect to an exemplary mixture of $U^{238}F_6$ and $U^{235}F_6$, from reactions (5) and (6) in accordance with the discussed constraints:

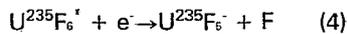


and

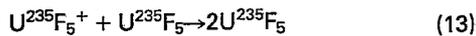


The positive $U^{235}F_5^+$ ion formed can accordingly be easily separated from the balance of the mixture, including $U^{238}F_6$, unreacted $U^{235}F_6$, and free fluorine and electrons, based upon increased mass difference principles. The separation factor S for this process is the same as that for production of the negative ion $U^{235}F_5^-$, 0.172.

Furthermore, the electrons produced in reaction (12) can, if produced at suitable energies, react with $U^{235}F_6^*$ as from reaction (4)



Therefore, the benefits of both selective dissociative ionization and selective dissociative electron attachment can both be achieved. The $U^{235}F_5^+$ and $U^{235}F_5^-$ can react under the influence of space charge in accordance with reaction (10) as:



The product $U^{235}F_5$ can be separated based upon the increased mass differential principle. The cross-section for the process of reaction (4) can be enhanced by varying the photon energy $h\nu$ such that the electrons ejected in reaction (12) are at suitable energies. The separation factor of the overall process of reaction (13) is also $S = 0.172$.

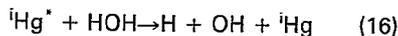
In yet another embodiment, referred to as photochemical enhancement of mass differential, a selective chemical reaction is utilized in conjunction with selective excitation. An endothermic chemical process can be generally described as:



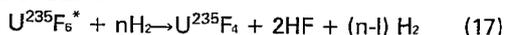
In reaction (14), the energy required can be identified as that of the excitation of X to a particular state or states. Further, this state is optically related to the ground state. Therefore, in accordance with the isotopic shift, XZ can be created in preference to 1XZ . For example, it has been shown by Pertel and Gunning (Can. J. Chem., Vol. 37, p. 35, 1959) that photo-excited isotopes of mercury can be preferentially reacted with water vapor as follows:



and



where i denotes a selected isotope. By analogy, it is expected that UF_6 can also be made to preferentially undergo the reaction:

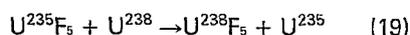


Accordingly, the $U^{235}F_4$ can be separated from the mixture based upon the increased mass differential.

It will be recognized that in all of the disclosed mass enhancement separation processes there is a finite probability that some of the selectively reacted isotopes may suffer in isotopic exchange with another isotope:



or, for example,



Since the mass separation system utilized will be based upon separation and recovery of the desired isotopic species prior to isotopic exchange of the type illustrated in reaction (18), such exchange is detrimental to the overall separation efficiency. Accordingly, the time between creating the desired species and its passage through the separating device is preferably minimized.

For example, the formation time t_f of the negative ion X^- in reaction (2) can be estimated to be

$$t_f = \frac{1}{k_a n_e} \text{ sec,}$$

where k_a is the dissociative electron attachment coefficient in cm^3/sec and n_e is the electron density in the reaction zone per cm^3 . The isotopic exchange time t_{ex} for reaction (18) is

$$t_{ex} = \frac{1}{K_{ex} [{}^1XZ]} \text{ sec,}$$

where K_{ex} is the exchange rate coefficient in cm^3/sec and $[{}^1XZ]$ is the density of the undesired isotopic species. The transit time t_t of the mixture passing through the exemplary device is

$$t_t = \ell/v$$

where ℓ is the length of the rotor or of the nozzle deflector and v is the velocity of the mixture passing into the nozzle. It is therefore desirable to maintain the relationship $t_r < t_r < t_{ex}$ in order to minimize isotopic exchanges.

I have therefore disclosed mass separation processes including methods for increasing the mass differential among isotopic species in a mixture. Many modifications and additions are possible in view of the above teachings. It therefore is to be understood that within the scope of the appended claims the invention can be practiced other than as specifically described.

CLAIMS

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1. A method for separating isotopic species in an isotopic mixture including a first species having a first isotope and a second species having a second isotope, wherein said first species is selectively excited in preference to said second species, characterized in that said selectively excited first species is then reacted with one of an electron, a preselected radiation and a chemical species so as to form a product including said first species which product has a mass different from said second species by a larger degree than said original first species; and said mixture is conducted through a centrifugal separating device wherein, as a result of the enhanced difference in mass, said product is separated from the balance of said mixture and follows a path different from the flow path of the balance of said mixture, both flow paths terminating in different outlets (38,40).

20

2. A method as claimed in claim 1, characterized in that said first species is a molecular compound including Uranium-235 and said second species is a molecular compound including Uranium-238.

25

3. A method as claimed in claim 1 or 2, characterized in that said selectively excited first species is reacted with a second radiation so as to promote selective dissociative ionization of said first species resulting in said product being a positive ion, said first selective excitation being means of narrow band photon irradiation of an ionization potential $h\nu_1$, wherein said second preselected radiation is by means of photon irradiation $h\nu_2$, said selected first species has an ionization potential V_1 , and $(V_1 - h\nu_1) < h\nu_2 < V_1$.

30

4. A method as claimed in claim 1, characterized in that one part of said selectively excited first species is exposed to a second predetermined radiation so as to promote selective dissociative ionization of said first species resulting in said part of said product being positively ionized, said product also including a neutral fragment and an electron; another part of said selectively excited first species is reacted with said product electron so as to promote dissociative electron attachment of some other of said first species resulting in some of said product being negative ions; and said negative ions are reacted with said positive ions so as to form a neutral species of increased mass.

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5. A method as claimed in claim 1, 2 or 3, characterized in that said selectively excited first species is reacted with another chemical species so as to form a neutral chemical compound.