Average charges of heavy recoil ions in various gases and their mixtures

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Introduction

- Gas filled separator-Average charges of heavy ions
- Semi-empirical expressions from BGS (LBNL, Berkeley), DGFRS (JINR, Dubna), GARIS (RIKEN, Wako)…

**TASCA**

- Determination of charges at different gas pressures of helium and hydrogen
- Use of gas mixtures (helium and hydrogen)
- Prediction of average charges in pure gases and mixtures

**Average charges of Nobelium ions produced in fusion-evaporation reactions** $^{48}\text{Ca}+^{206-208}\text{Pb}$

- $^{48}\text{Ca}$ from ECR ions source, 5 ms pulse with 50 Hz frequency from UNILAC was used
- Three segments of lead sulfide (PbS) targets (ARTESIA type) with thicknesses of about 550 µg/cm² on 2.2µm Ti foils was used
Experimental setup
TransActinide Separator and Chemistry Apparatus
TASCA

M. Schädel et al., GSI Scientific Report 2005, GSI, Darmstadt, Germany, Report 2006-1, 2006, p. 262; see also http://www.gsi.de/TASCA
TransActinide Separator and Chemistry Apparatus
TASCA

material: Si
active area: 80x35 mm²
thickness: 300 µm
position resolution: 200 µm
Strips: 16
Energy spectra from the reaction $^{48}$Ca+$^{206}$Pb
(HTM, $(B\rho)_0=2.08$ TM, $P_{He}=0.8$ mbar)

Low energy

High energy

Beam off

Beam off
Distribution of detected events which have different origins

**Transmission:**
\(\alpha^{\left(252\text{No}\right)}\) and \(SF^{\left(252\text{No}\right)}\)→EVR\(^{\left(252\text{No}\right)}\)

**Target-like ions:**
Events with \(E=(20-100)\) MeV

**Beam-like ions:**
Events with \(E>100\) MeV

Main counting rate on the detector produced by target-like and beam-like ions.
Average charges in pure He and H\textsubscript{2}
Dependence of the EVR's distributions on the gas pressure

HTM, $^{48}$Ca$+^{206}$Pb, $(B\rho)_0=2.07$ Tm

Real magnetic rigidity of EVR’s

$$(B\rho)_{ion} = (B\rho)_0 \times \left\{ 1 + \frac{x}{100 \cdot D} \right\}$$


$(B\rho)_0$-magnetic rigidity of separator

$$(B\rho)_{ion} = 0.0227 A \left( \frac{v/v_0}{q} \right)$$

$v$-was estimated in the middle of dipole magnet using the PACE2, TRIM and table of L. C. Nortiicilffe for reaction kinematics, energy loss of ER's in target and gas, respectively.
Dependence of the EVR's distributions on the gas pressure

HTM, $^{48}\text{Ca}+^{206}\text{Pb}$, $(B\rho)_0=2.07$ Tm

Our measured average charges were in agreement with calculated ones within error bars. Semi-empirical formulas were taken from K.E. Gregorich et al., PRC. 72 (2005) 014605. and Yu.Ts. Oganessian et al., PRC. 64 (2001) 064309.
“Density effect”

\[ q_{ion} = \bar{q} + \Delta q \]
\[ \Delta q = \frac{\bar{q}}{5} \]

The maximum density effect was estimated by Bohr and Lindhard as 20%.


In order to explain the experimental results on the density effect obtained by Lassen (1951a, b), Bohr and Lindhard (1954) describe a simplifying model for the excitation and de-excitation of fission fragments. They derive an expression for the increase of the average equilibrium charge as a function of the target gas density

\[ \Delta \bar{q} = (\beta_i + \beta_c) \tau \nu \sigma_t \rho / [ (\alpha_i + \alpha_c) (2 \tau \nu \sigma_t \rho + 1) ] \], \quad (6.9) \]

where \( \tau \) is the lifetime under investigation, \( \nu \) the ion velocity, \( \rho \) the density of the target gas, and \( \sigma_t \) the total charge-changing cross section which, in fact, stands for the effective excitation cross section. For

**Fit functions**

\[ q_{ion} = \bar{q} + \frac{a}{b + y} \]

Where \( y \) is a variable determined as \( y = [(\nu/\nu_0) \cdot P]^{-1} \)

P is the gas pressure

\[ (B \rho)_{ion} = \frac{a + b \cdot y}{c + y} \]
Magnetic rigidities and average charges of No ions at different gas pressures

Mean charges have linear dependences on velocities

$$\bar{q} = Z^{1/3} \cdot (v / v_0)$$

for $1 < (v/v_0) < Z^{2/3}$

$$ (B\rho) = 0.0227 \times \frac{A}{Z^{1/3}} \ [Tm] $$

Magnetic rigidity does not depend on initial velocity and charge state

Use of the magnetic rigidity for the determination of "density effect". Similar behavior of curves for $^{254}$No and $^{252}$No ions in the helium gas means that influence of "density effects" to these ions are same. This could be due to the same charge-exchange cross-sections (these ions have same atomic shells).
Average charges in the mixture of He and H$_2$
Magnetic rigidities and average charges of $^{254}$No ions in the gas mixture

We know: $(B\rho)_{\text{ion}}$ for pure helium and hydrogen depends on gas pressure!

Ratio of gases $v=n_{\text{He}}/n_{\text{H2}}$
Magnetic rigidities and average charges of $^{254}$No ions in the gas mixture

How we can predict the magnetic rigidities in the gas mixtures?

In the present experiments the velocities of EVR's ($^{254}$No) were within the regions:

- Helium: $(v/v_0)=2.41\pm0.03$
- Hydrogen: $(v/v_0)=2.36\pm0.03$
- Mixture: $(v/v_0)=2.39\pm0.03$

We know: $(B\rho)_{ion}$ for pure helium and hydrogen depends on gas pressure!

Ratio of gases $v=n_{He}/n_{H2}$
Mathematical description of the charge-exchange process

$$\frac{dF_i(n)}{dx} = \sum_{j, j \neq i} \left[ \sigma_{ij} \cdot F_j(n) - \sigma_{ji} \cdot F_i(n) \right]$$

$\sigma_{ij}$ - electron capture cross-section

$\sigma_{ji}$ - electron loss cross-section

$n$ - number of particles per square centimeter traversed by the heavy ion

If $dF_i(n)/dx \rightarrow 0$ than charge states of heavy ions will be equilibrated!

Charge state - $i$
Fraction – $F_i$
$\sum F_i = 1$

$F_i^{mix} = F_i \cdot P_{He} + F_i \cdot P_{H_2}$

$\sum_i F_i^{mix} = \sum_i [F_i \cdot P_{He} + F_i \cdot P_{H_2}] = 1$

$\bar{q}_{mix}^{(n_{tot})} = q_{He}^{(n_{tot})} \cdot P_{He} + q_{H_2}^{(n_{tot})} \cdot P_{H_2}$

Weighted mean value!!

$n_{tot}$- total number of atoms

$\bar{q}_{mix}^{(n_{tot})} = P_{He} \cdot \sum_i q_i \cdot F_i + P_{H_2} \cdot \sum_i q_i \cdot F_i$

$\left( B\rho \right)_{ion}^{mix} (n_{tot}) = \frac{(B\rho)_{ion}^{He} (n_{tot}) \cdot (B\rho)_{ion}^{H_2} (n_{tot}) \cdot (1+\nu)}{(B\rho)_{ion}^{He} (n_{tot}) \cdot (\nu / \nu_0)_{H_2} + (B\rho)_{ion}^{H_2} (n_{tot}) \cdot (\nu / \nu_0)_{He} \cdot \nu} \cdot (\nu / \nu_0)_{mix}$
Magnetic rigidities of $^{254}$No ions in the gas mixture

With increasing of the gas ratios the magnetic rigidities are changing.

If $\nu = n_{He}/n_{H2} > 1$ increase then 

$$(B\rho)_{mix} \rightarrow (B\rho)^{He}$$

If $\nu = n_{He}/n_{H2} < 1$ decrease then 

$$(B\rho)_{mix} \rightarrow (B\rho)^{H2}$$
Average charges of $^{254}$No ions in the gas mixture

With increasing of the gas ratios the average charges are changing.

If $\nu = n_{He}/n_{H2} > 1$ increase then

\[(q)_{mix} \rightarrow (q)^{He}\]

If $\nu = n_{He}/n_{H2} < 1$ decrease then

\[(q)_{mix} \rightarrow (q)^{H2}\]
Summary and conclusions

• Magnetic rigidities and average charges of No’s were determined in the He, H₂ and mixtures of them.

• Average charges of heavy ions (EVR's) are changing depend on the gas pressure of pure He and H₂.
• This effect can be attributed to the so called "density effect".
• Average charges of heavy ions can be determined by the semi-empirical expression (i).

• The expression for the determination of average charges of heavy ions in the gas mixture is given (ii)

• Experimentally determined magnetic rigidities and average charges well predicting by using the (i) and (ii) at different gas pressures and mixtures

"Density effect" and gas mixtures should be studied in “more” heavy ion reactions and also it could be tested for the improvement of transmissions and suppression factors for various kind of reactions. It also should be included to the ion optical simulation programs.